Structures in the cosmos: What they tell us about neutrinos and warm dark matter

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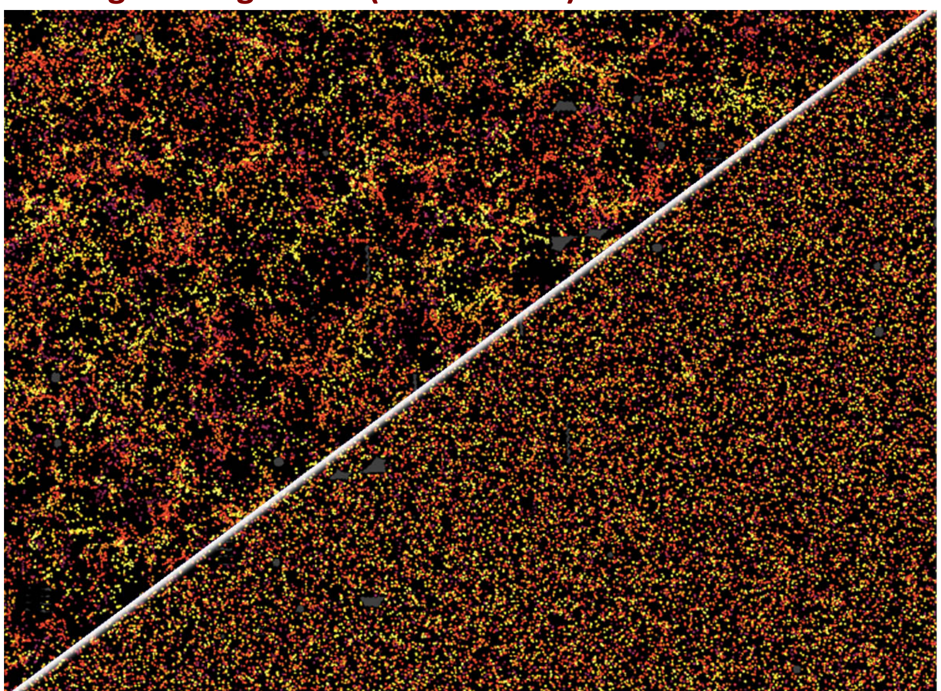
CEA-Saclay (IRFU/DPhP)

500 deg^2 BOSS galaxies (0.50<z<0.55)



500 deg^2 random (0.50<z<0.55)

Sloan: a clustering saga

→ Primary cosmological goals
- **BAO (dark energy)**
- **RSD (gravity)**

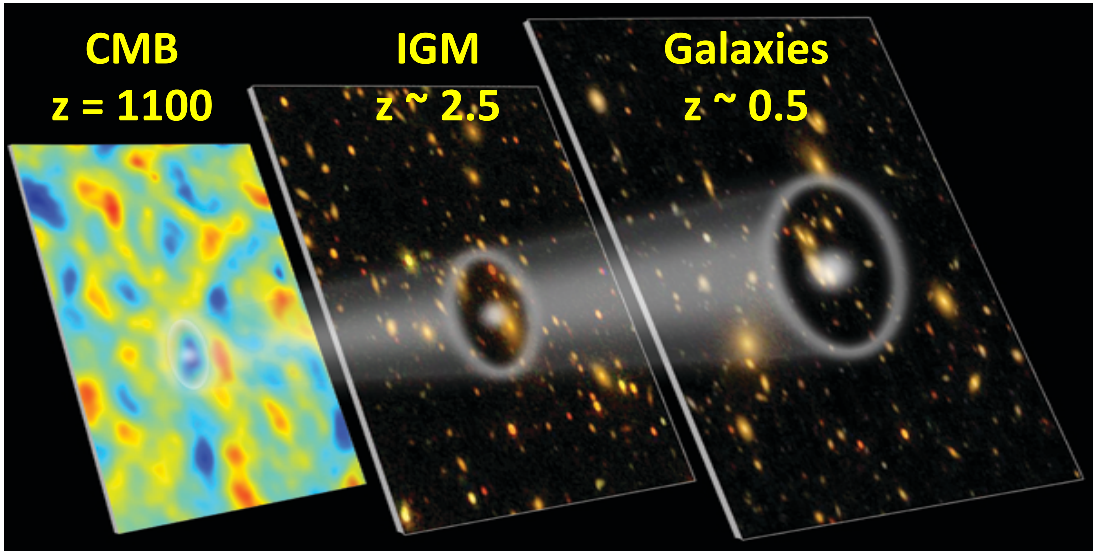
→ Additional goals
- **Free-streaming cutoffs**

BOSS & Lyman-α

Constraining Σm_ν

Nature of dark matter

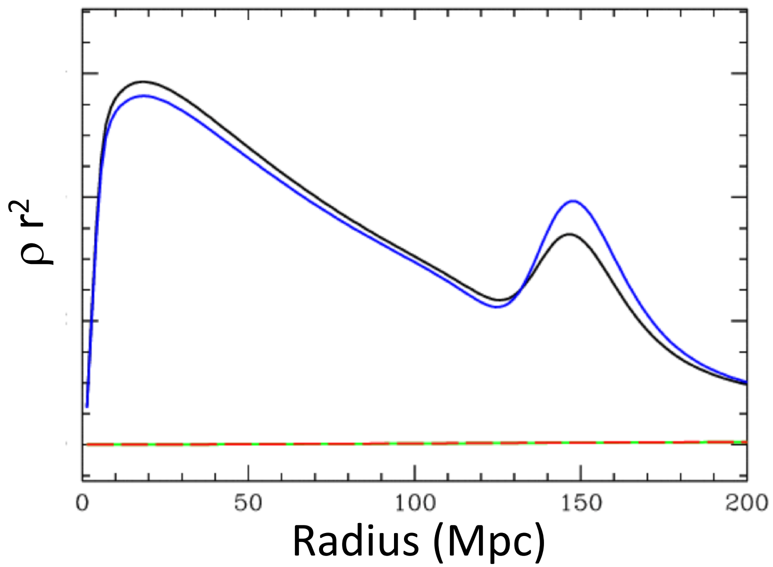
Baryon Acoustic Oscillations (BAO)

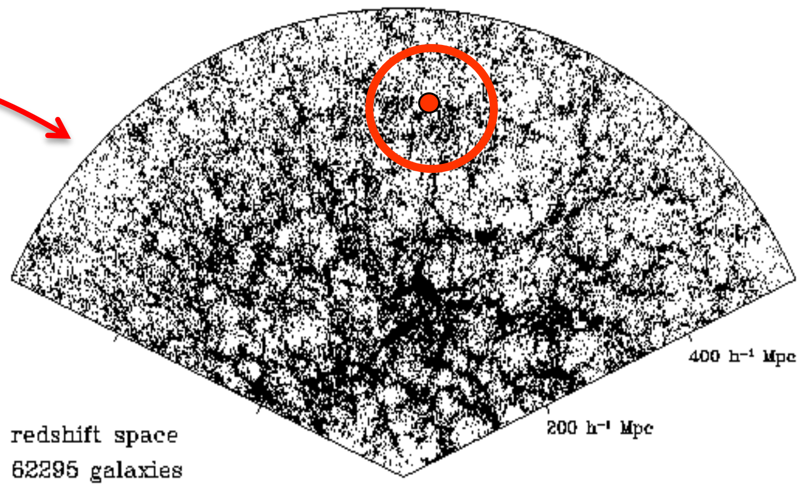


Propagation of baryon-photon overdensity wave in plasma

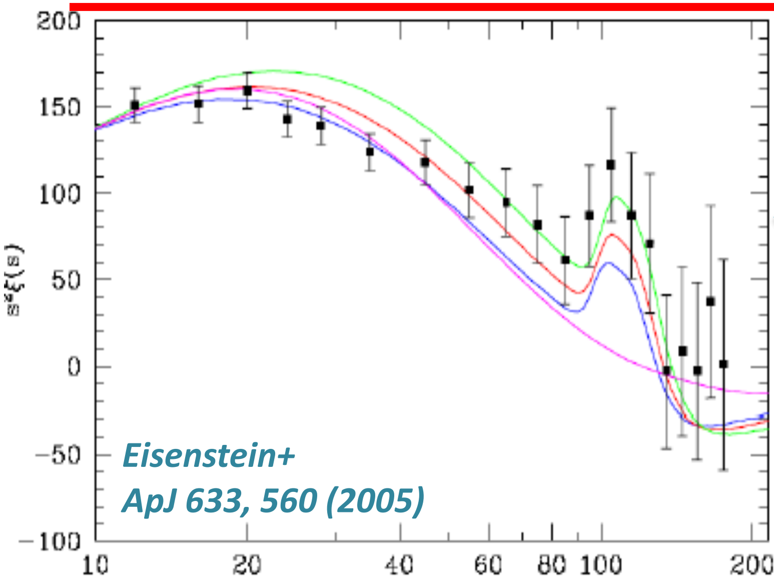
Wave frozen at recombination, at comoving r_s ~ 150 Mpc

Standard ruler in LSS
A preferred 3D scale





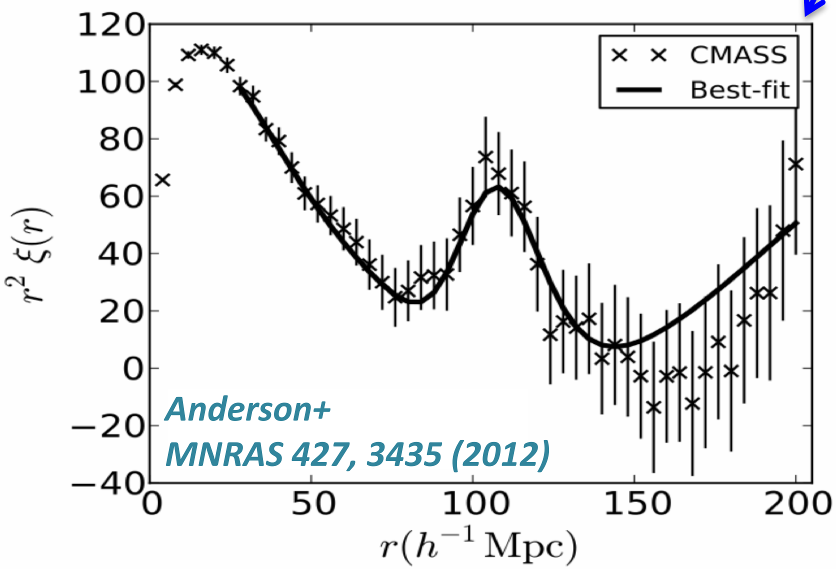
Baryon Acoustic Oscillations (BAO)



Observations

2005: First detection of BAO peak

2012: 5σ confirmation by BOSS



Baryon Acoustic Oscillations (BAO)

Observations

2005: First detection of BAO peak
2012: 5σ confirmation by BOSS
2014: First 3D measurements of BAO

Transverse direction

$\Delta\theta = r_s / [(1+z)\, D_A(z)]$

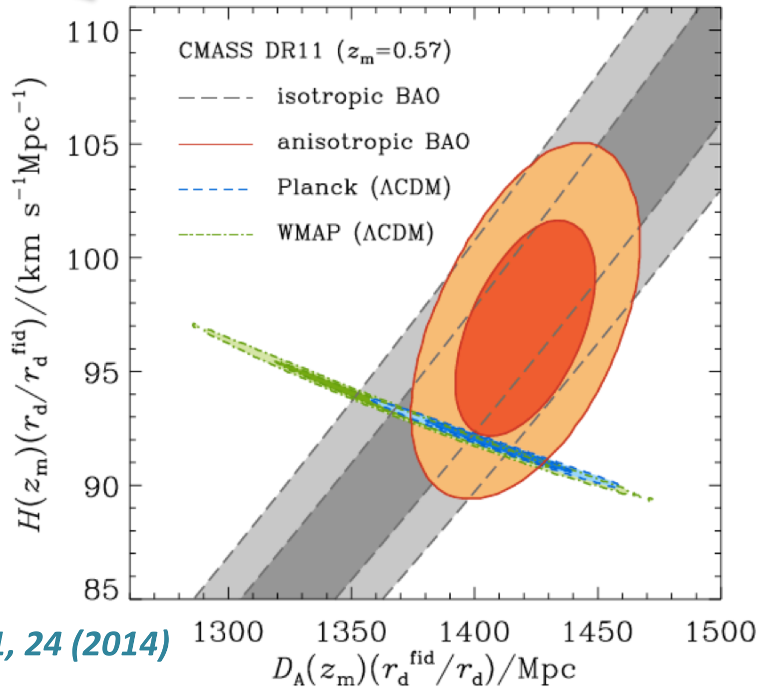
$\Rightarrow$ Angular distance $D_A(z)$

as SNIa: $D_L(z) = (1+z)^2\, D_A(z)$

Radial direction (along line of sight)

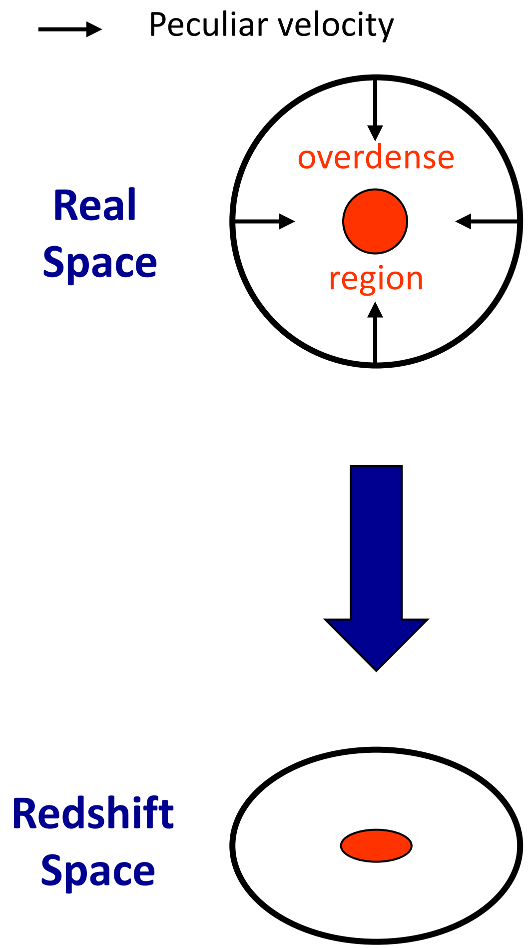
$\Delta z = r_s\, H(z) / c$

$\Rightarrow$ Hubble parameter $H(z)$



Anderson+ MNRAS 441, 24 (2014)

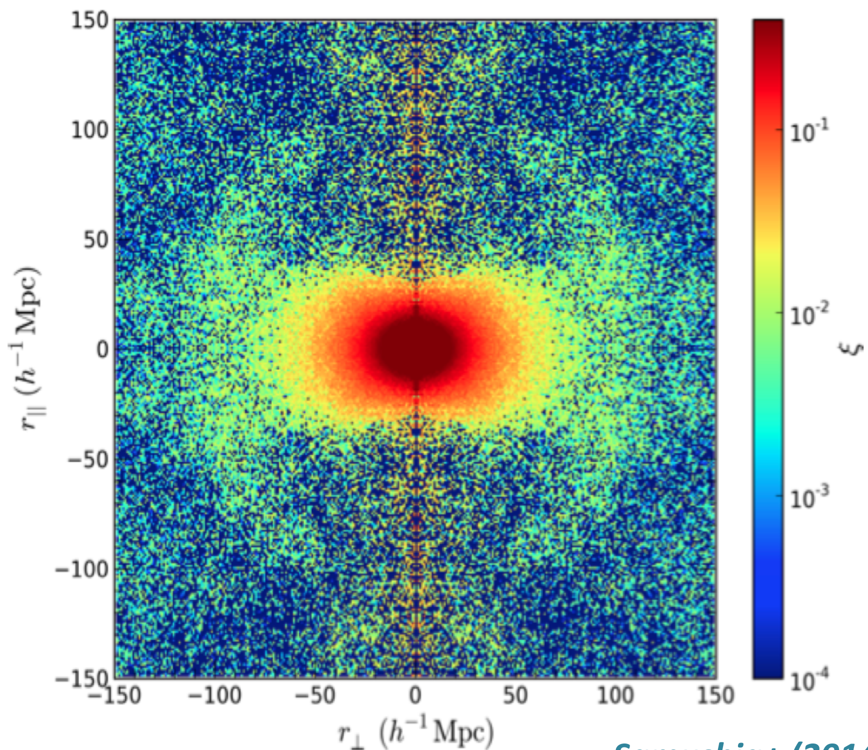
Redshift Space Distortion



Measure of gravitational growth

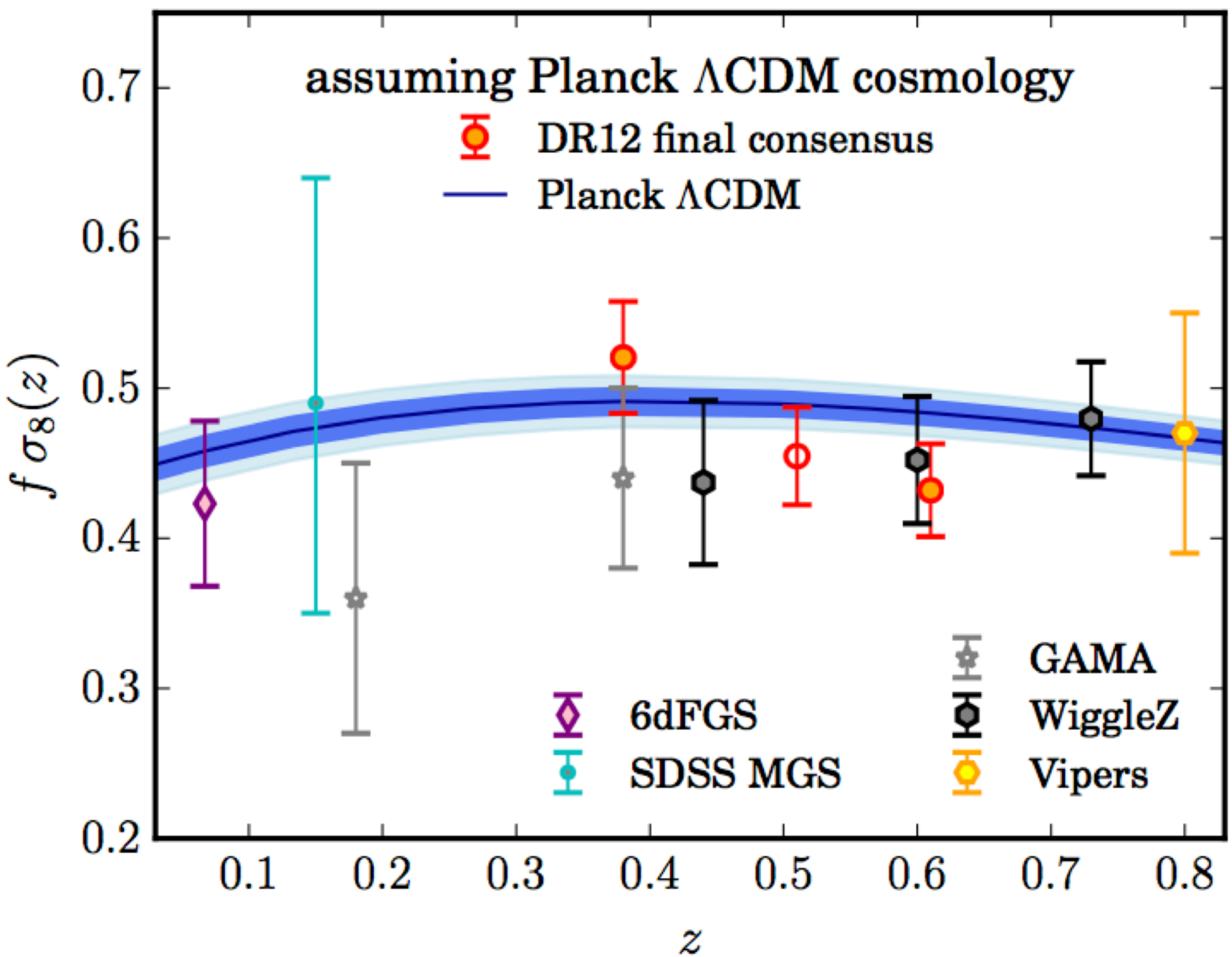
$$P_F(k) = b_F^2 \times \left[1 + \beta \cos(\theta)^2\right]^2 \times P_L(k)$$

$$\beta \rightarrow f\sigma_8$$



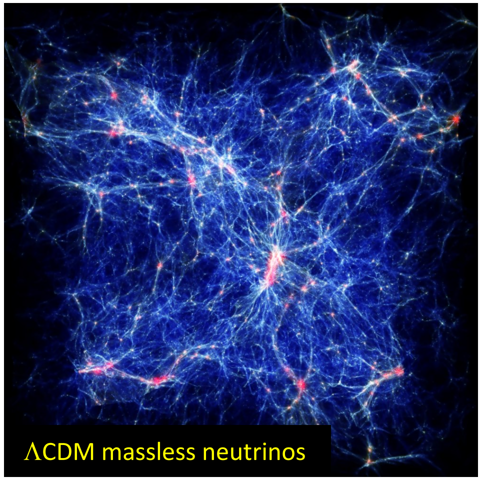
Samushia+ (2014)

Redshift Space Distortion



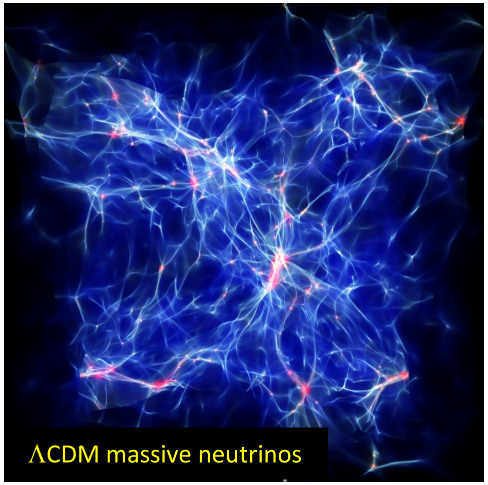
Alam+ (2016)

Small-scale clustering and free streaming



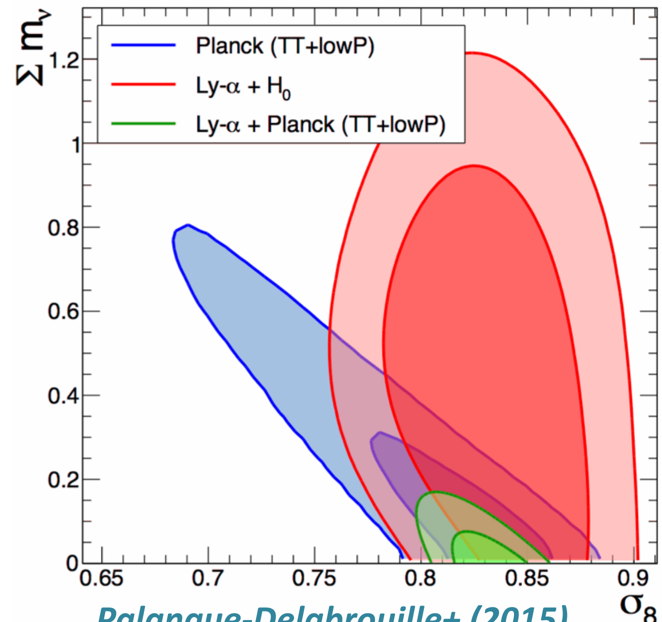
Free streaming of relativistic particles (hydrodynamical simulations)

Suppression of small scales



Suppression depends on particle mass

Constraint on $\Sigma m\nu$
Constraint on mass of warm dark matter



Palanque-Delabrouille+ (2015)

Structures in the Sloan

Sloan: a clustering saga

- **Primary cosmological goals**
  - **BAO (dark energy)**
  - **RSD (gravity)**
- **Additional goals**
  - **Free-streaming cutoffs**

BOSS & Lyman-α

Constraining neutrino mass

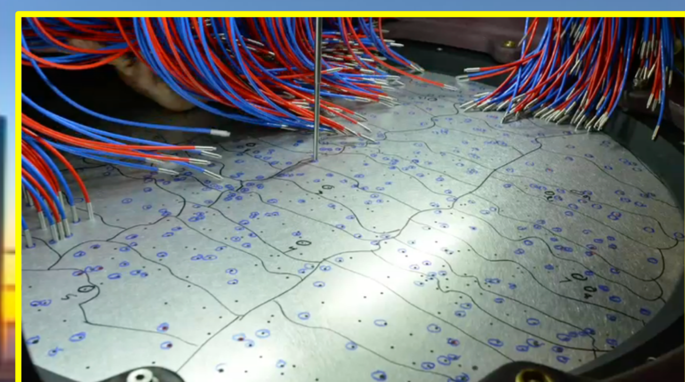
Studying the nature of dark matter

Sloan Digital Sky Survey

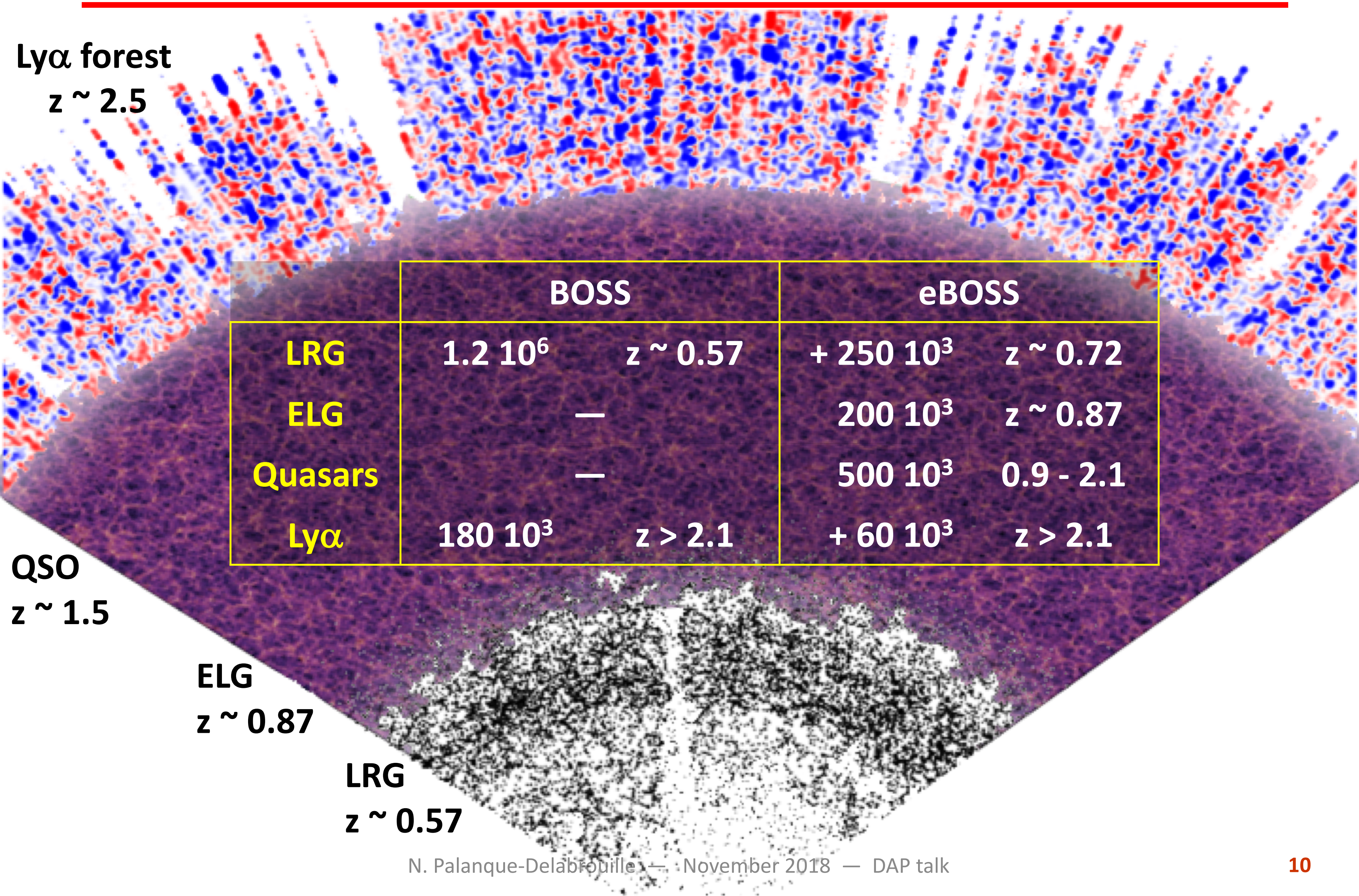
- **2.5m telescope**
  (New Mexico)

- **3D map of structures**
  - (α,δ) from
  BOSS: 10 000 deg^2
  eBOSS: 7 500 deg^2
  - z from 1000 fibers

BOSS 2009-2014
eBOSS 2014-2020

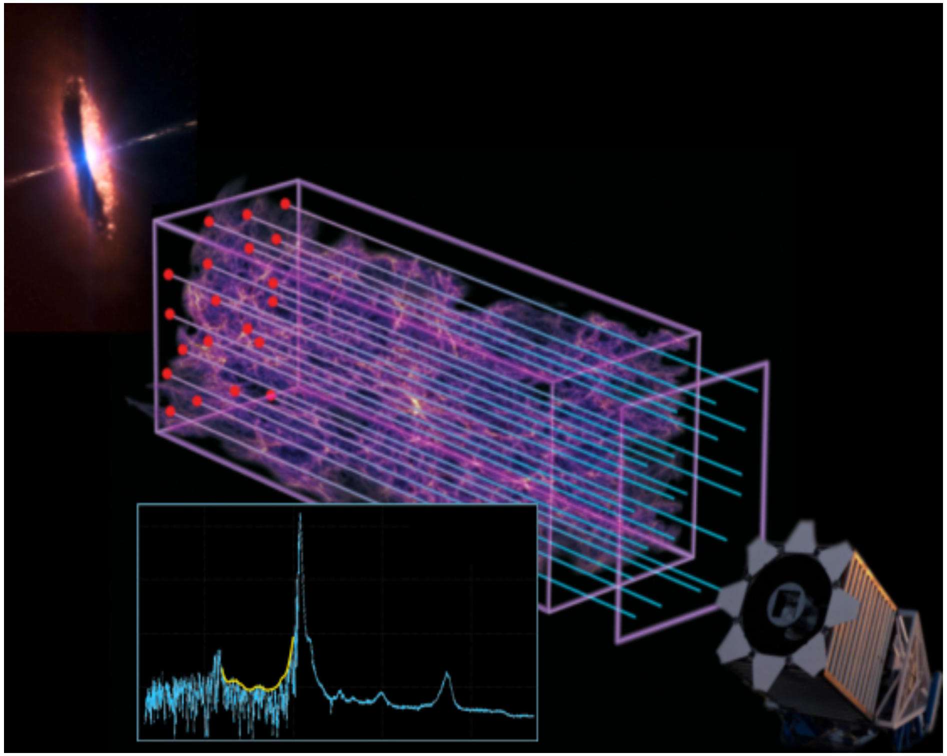


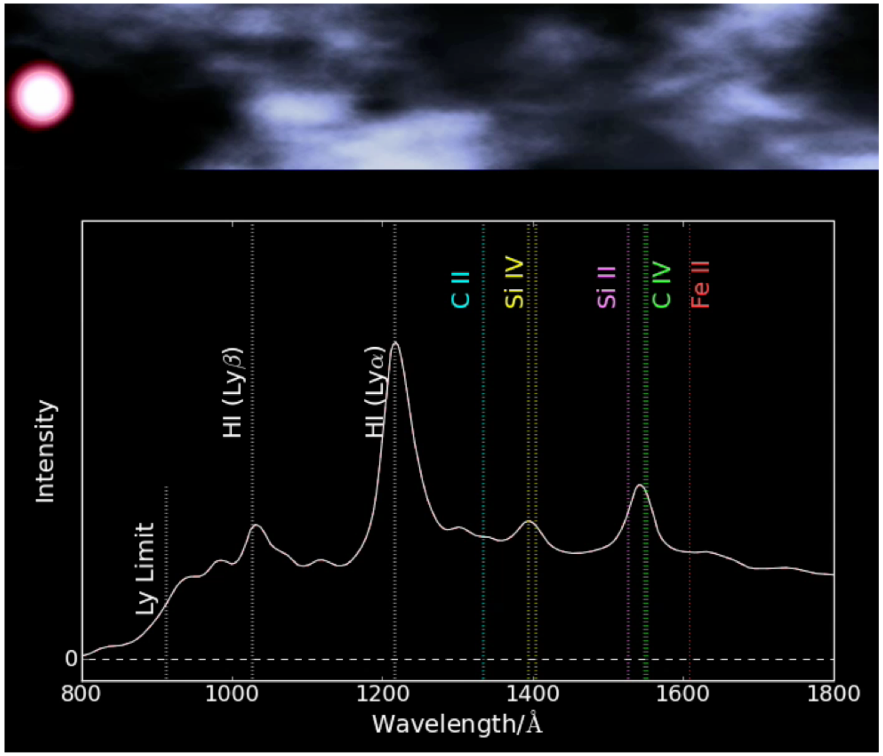
Sloan BOSS and eBOSS



	BOSS		eBOSS	
LRG	$1.2\ 10^6$	z ~ 0.57	+ $250\ 10^3$	z ~ 0.72
ELG	—		$200\ 10^3$	z ~ 0.87
Quasars	—		$500\ 10^3$	0.9 - 2.1
Lyα	$180\ 10^3$	z > 2.1	+ $60\ 10^3$	z > 2.1

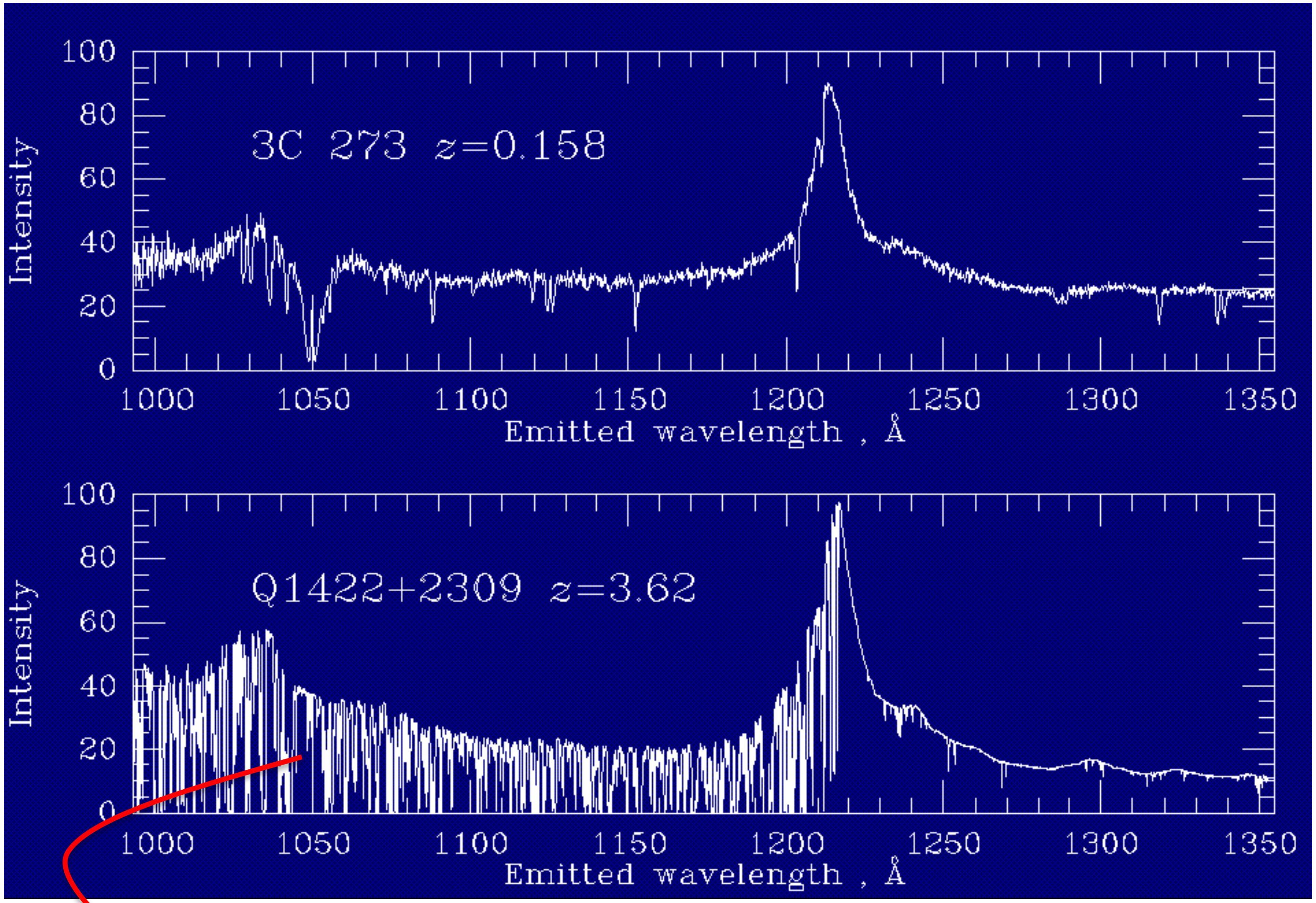
Lyα forest





- Quasars visible to high redshift (z ~ 5)
- Absorption by neutral H (IGM) on light path
- IGM probes matter density
- Matter distribution on small scales (ν, ν_s)
- 1D Power spectrum (along line of sight)

Lyα forest

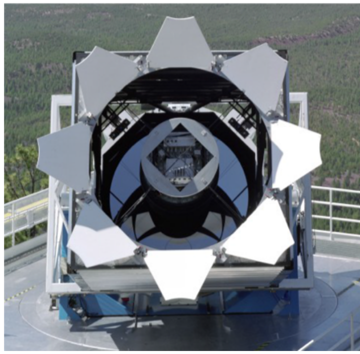


Small density of neutral H
in local Universe
(~fully ionized)

Higher density of neutral H
in distant Universe

Transmitted flux fraction: $\delta = \frac{f - \langle f \rangle}{\langle f \rangle}$

Lyα forest 1D power spectrum



Selection of ~14 000 out of 60 000 z>2.1 BOSS QSOs

Detailed study of contributions from

- **detector (spectrograph resolution, noise)**
- **astrophysics (sky lines, correlation with other absorbers)**

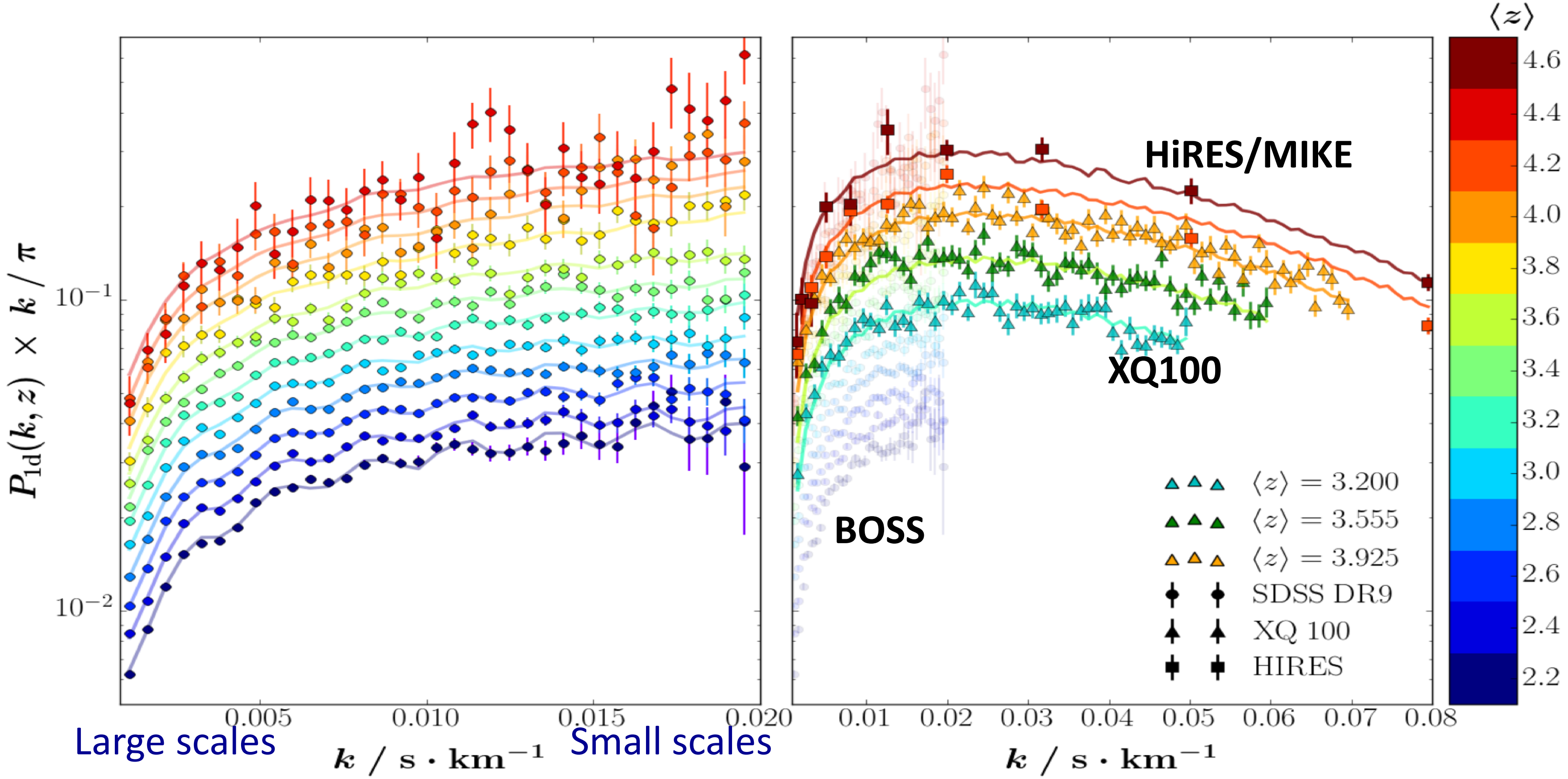
$$P_{Raw}(k) = [P_{Ly\alpha}(k) + P_{Lya\text{-}SiIII}(k) + P_{metals}(k)] \times W^2(k) + P_{Noise}(k)$$

Lyα forest 1D power spectrum

BOSS
NPD, Yeche+ (2013)
12 bins z=2.2 to 4.4

XQ100
Yeche, NPD+ (2017)
Irsic, Viel+ (2017)
z=3.2, 3.6, 3.9

HiRES/MIKE
Viel, Becker+ (2013)
z=4.2, 4.6, (5.4)



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BOSS & Lyman-α

Constraining neutrino mass

Studying the nature of dark matter

Why ν's have mass

Neutrino oscillations ⇒ ν's are massive

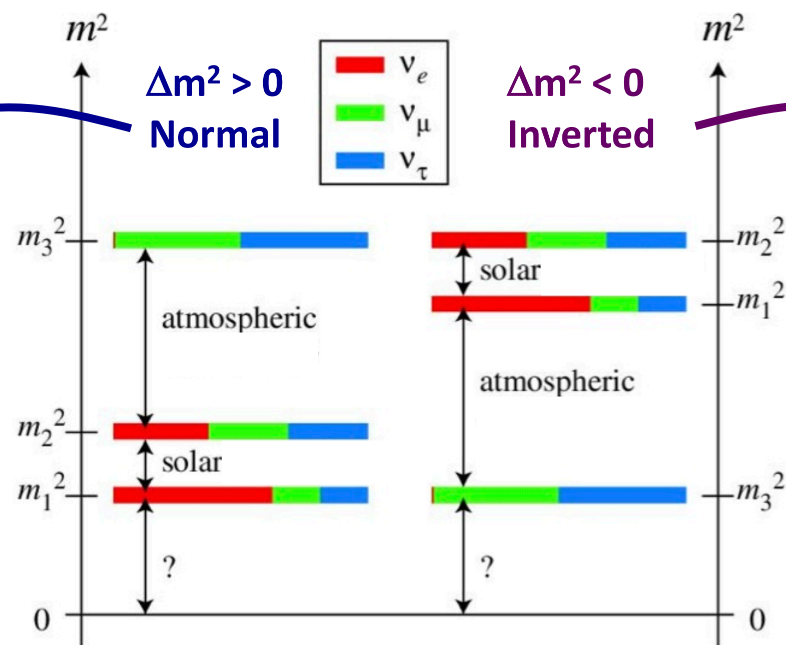
Solar	δm^2	$\sim 7.5\ 10^{-5}\ eV^2$
Atmospheric	Δm^2	$\sim 2.4\ 10^{-3}\ eV^2$

Direct m_ν detection from Tritium β decay

$m_e < 2$ eV

$0.06\ eV < \Sigma m_\nu < 6\ eV$

$\Sigma m > 0.06$ eV



$\Sigma m > 0.10$ eV

Why ν's have mass

In Universe, n_ν ~ n_γ ~ 3. 10^9 n_p

⟹ even for m_ν ~ 0.1 eV = 10^{-10} m_p
total ν mass ($n_\nu m_\nu$) of order total stellar mass ($n_p m_p$) !

⟹ **Can cosmology help?**

m_ν & large-scale structures

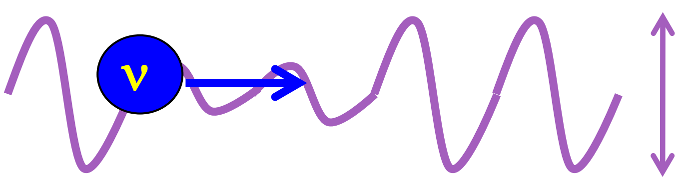
Neutrinos are relativistic early on
Neutrinos "free stream" at v=c until t_{nr} (actually once they have decoupled)

⇒ **Smooth perturbations of wavelength $\lambda < ct_{nr}$**
although normal clustering on scales $\lambda > ct_{nr}$

- **Heavy neutrinos (t_{nr} early)**

  Strong suppression over **short** range

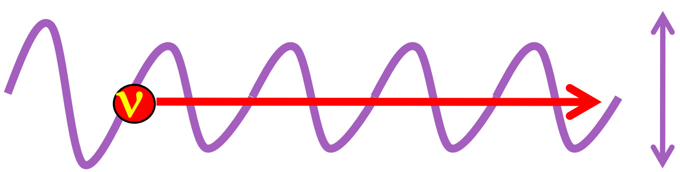
  m_ν ~ keV ⟹ size of dwarf galaxy perturbations smoothed out



- **Light neutrinos (t_{nr} late)**

  Weak suppression over **long** range

  m_ν ~ eV ⟹ size of galaxy cluster perturbations smoothed out



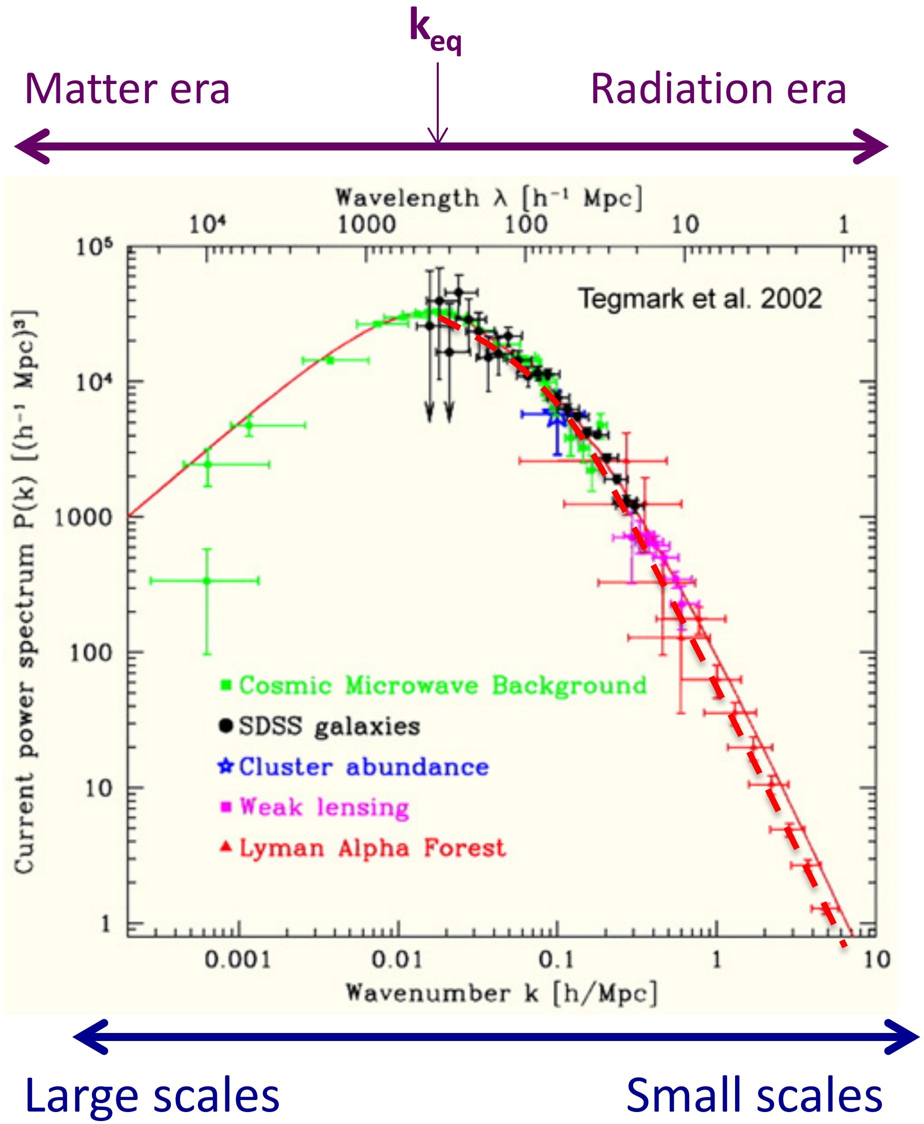
Impact of m_ν on large-scale structures

Matter power spectrum

Real-space (Mpc) ⟷ k-space (Mpc^{-1})

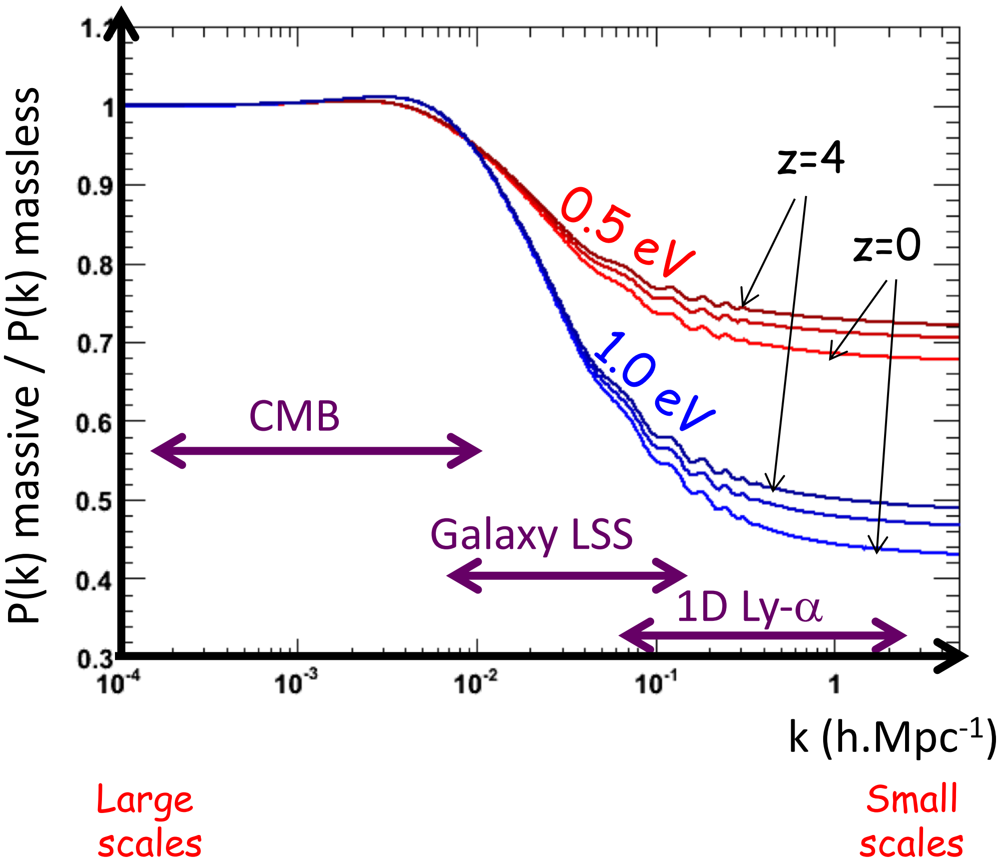
Causality horizon ↗ with time
- Early events ⟷ small scales
- Late events ⟷ large scales

Free-streaming
of relativistic ν's further
suppresses power on small scales



Neutrinos and large-scale structures

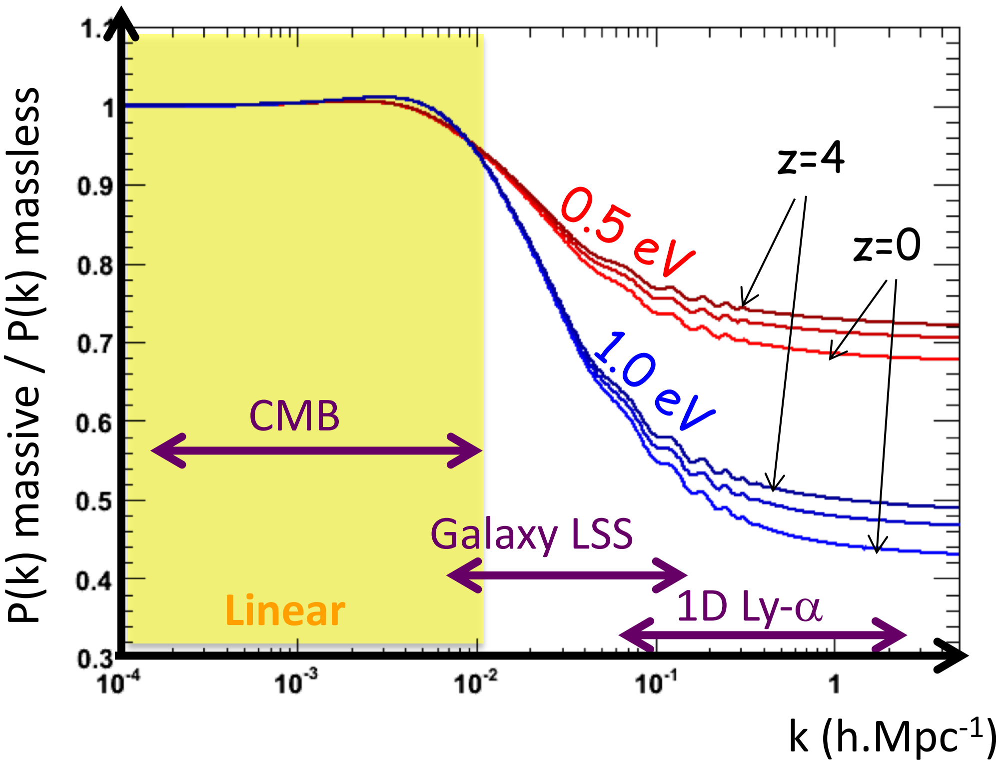
Different probes ⇔ different scales



- Suppression factor ⇔ Σmν
- Suppression is z-dependent
- **Ly-α**
  - Small scales, max effect ✚
  - Large z-range [2.1 ; 4.5] ✚

Neutrinos and large-scale structures

Different probes ⟺ different scales



Large scales

Small scales

- Suppression factor ⟺ Σmν
- Suppression is z-dependent
- Ly-α
  - Small scales, max effect +
  - Large z-range [2.1 ; 4.5] +
  - Non-linear regime, flux (not mass) P(k) ⇒ Hydro simulations −

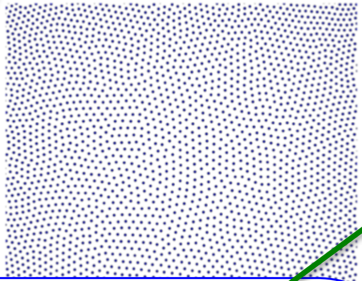
Hydrodynamical simulations

(100 h^{-1}Mpc)^3 with *3072^3* particles/species

McDonald (2003) splicing approach

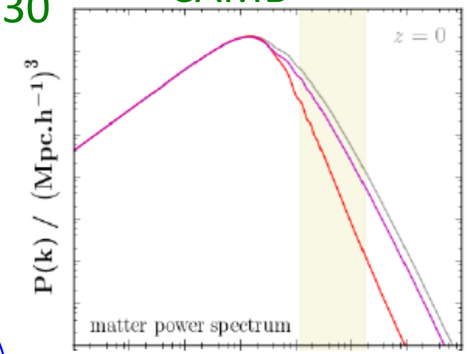
- dark matter
- baryons
- (degenerate-mass) neutrinos

2LPTic



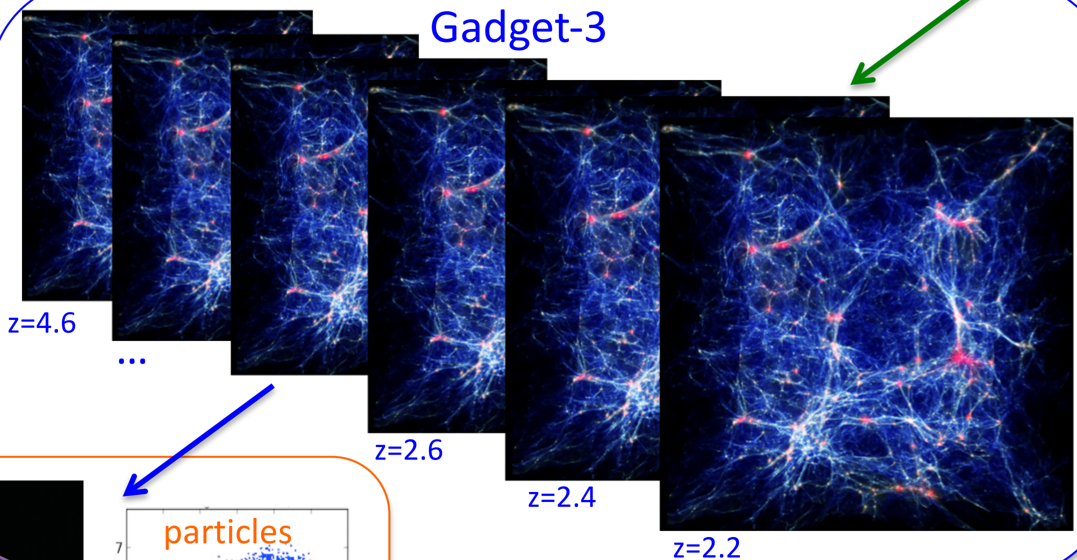
z=30

CAMB

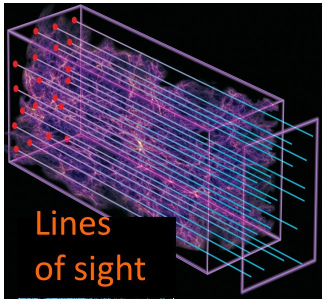


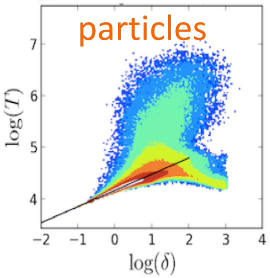
Initial conditions

Gadget-3



N-body + SPH simulation





Ly-α power spectrum

Borde, NPD et al. (2014)

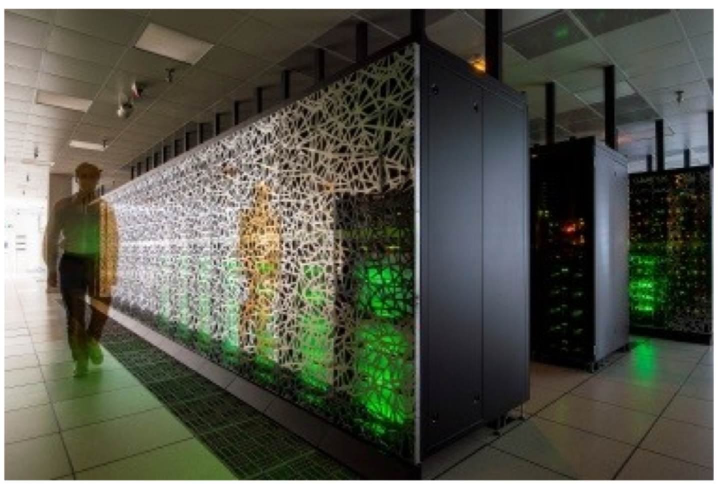
Rossi, NPD et al. (2014)

Hydrodynamical simulations

Grid of simulations

→ 2nd-order Taylor expansion for cosmo & astro parameters centered on Planck (2013)

$$
\begin{aligned}
f(\mathbf{x}+\Delta\mathbf{x}) &= f(\mathbf{x}) + \sum_i \frac{\partial f}{\partial x_i}(\mathbf{x})\Delta x_i \\
&+ \frac{1}{2}\sum_i\sum_j \frac{\partial^2 f}{\partial x_i \partial x_j}(\mathbf{x})\Delta x_i \Delta x_j
\end{aligned}
$$



TGCC Bruyères-le-châtel

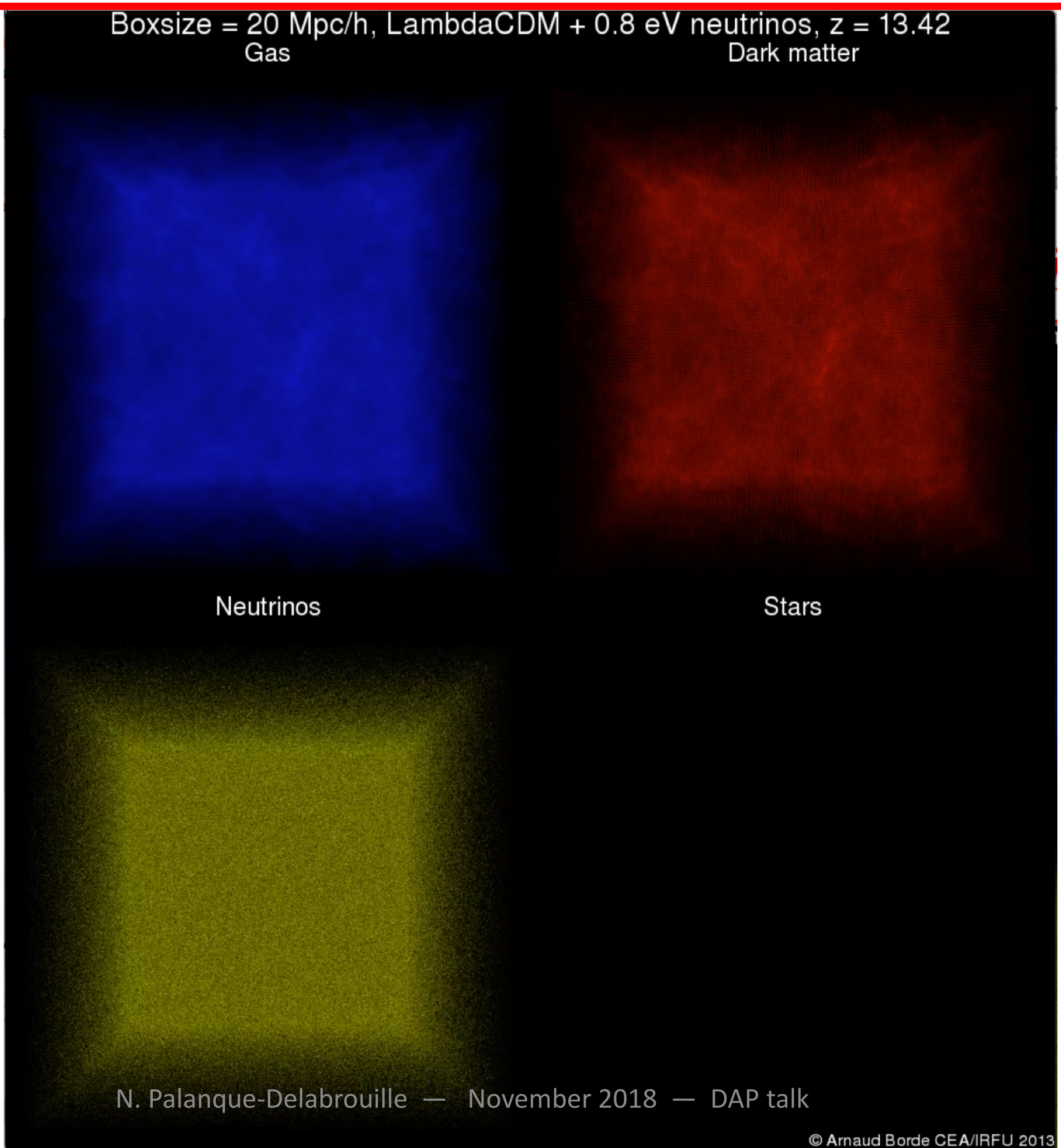
group	*parameter*	*central*	*range*
Cosmology	keV / m_X	0.0	+0.2 +0.4
Cosmology	$\Sigma m_\nu / eV$	0.0	+0.4 +0.8
Cosmology	h	0.675	±0.05
Cosmology	Ω_M	0.31	±0.05
Cosmology	σ_8	0.83	±0.05
Cosmology	n_s	0.96	±0.05
Cosmology	$dn_s / d\ln k$	0.00	±0.04
Cosmology	z_{reio}	12	±4
Cosmology	N_{eff}	3.046	±1
Intergalactic Medium	$T_0^{z=3} / K$	14,000	±7,000
Intergalactic Medium	$\gamma^{z=3}$	1.3	±0.3
Optical Depth	A^τ	0.0025	±0.0020
Optical Depth	η^τ	3.7	±0.4

Hydrodynamical simulations

z = 15 → 0

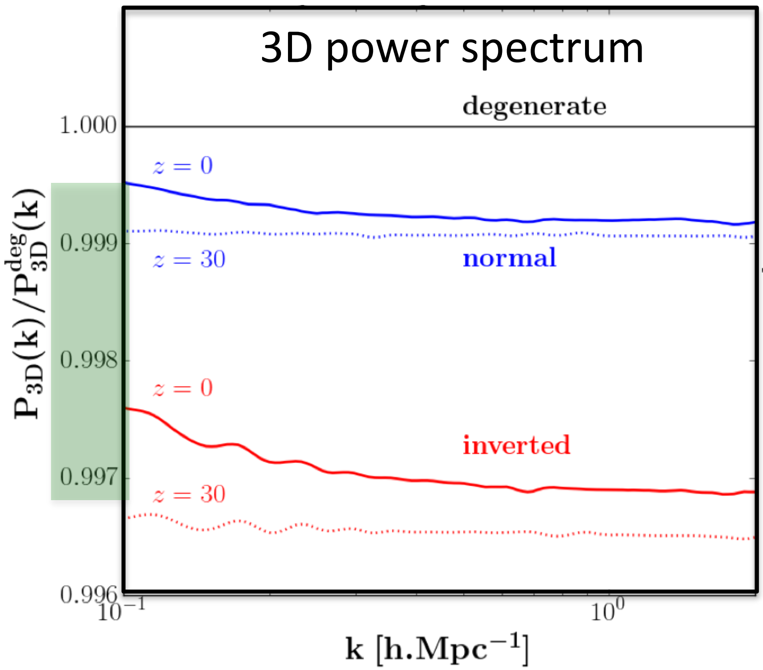
3 species
- Baryons
- Dark matter
- Neutrinos

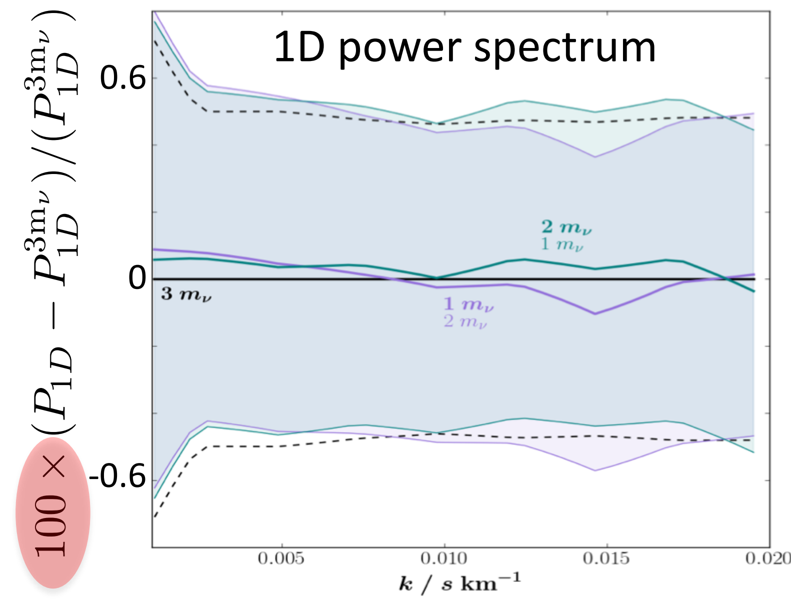
Stars formed from baryons



@ A. Borde (CEA-Saclay)

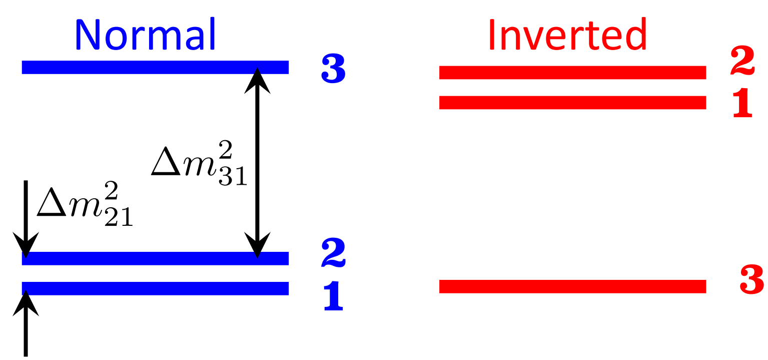
Neutrino mass (Σm) or masses (m_i)?





Hierarchy	m_1	m_2	m_3
Degenerate	0.033	0.033	0.033
Normal	0.022	0.024	0.055
Inverted	0.0007	0.049	0.050

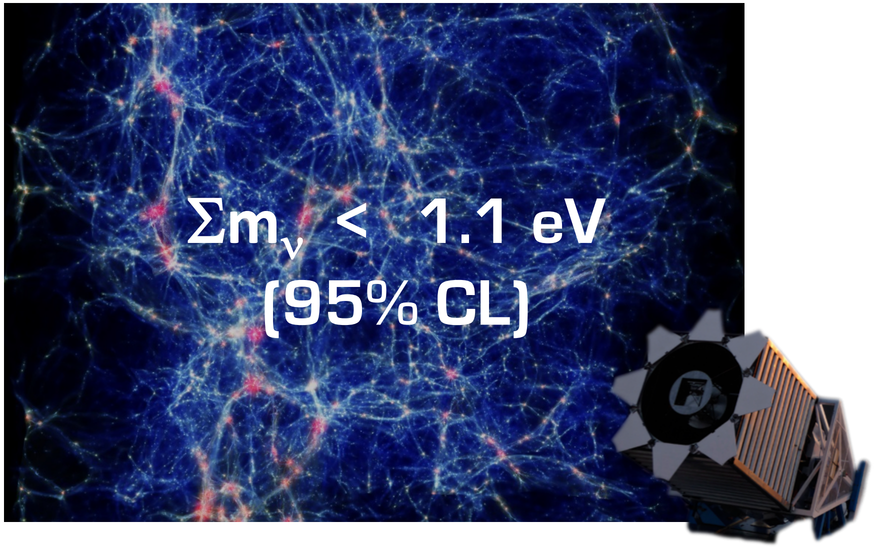
Σm = 0.10 eV



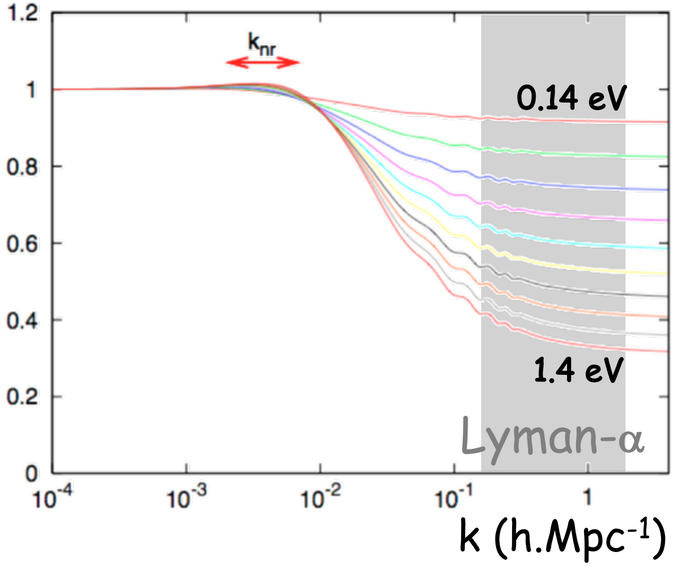
NPD, Yeche, Baur+ (2015)

‘Exclusively’ a Σm effect

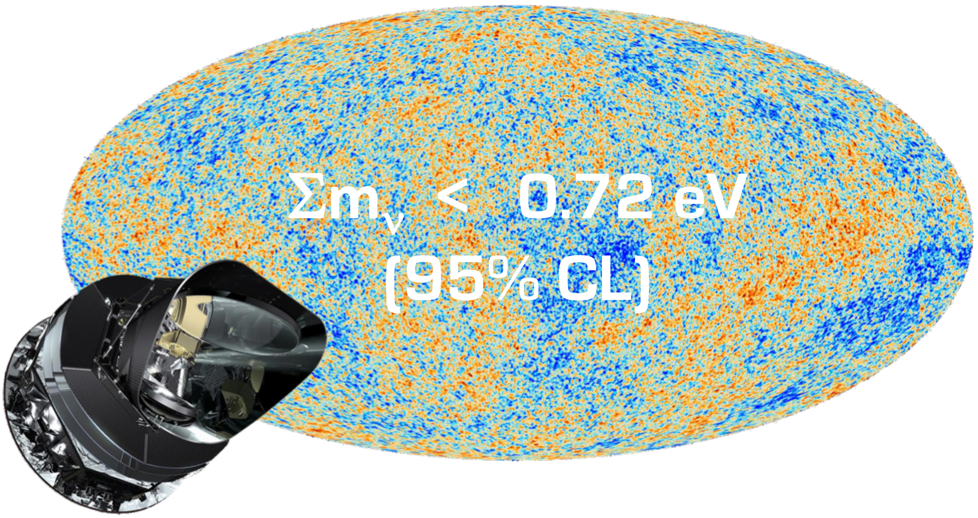
M_ν constraint

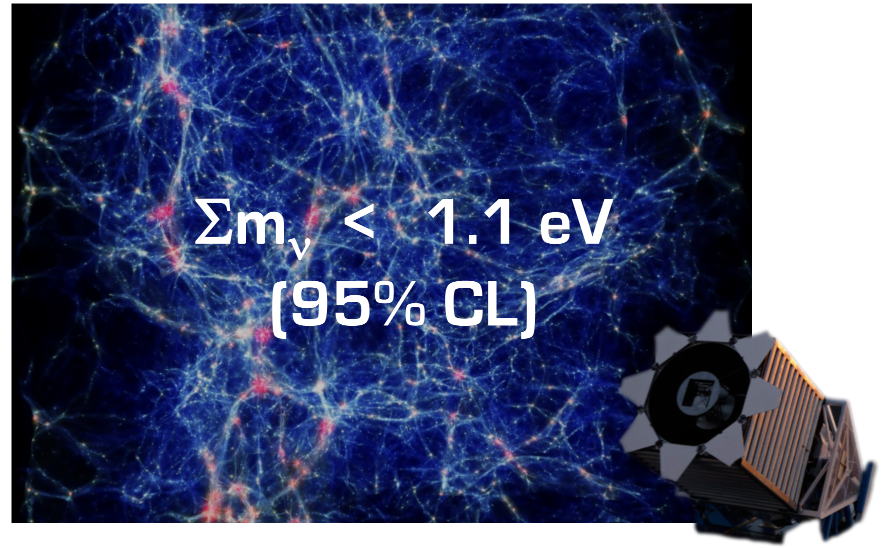


P(k) massive / P(k) massless



M ν constraint





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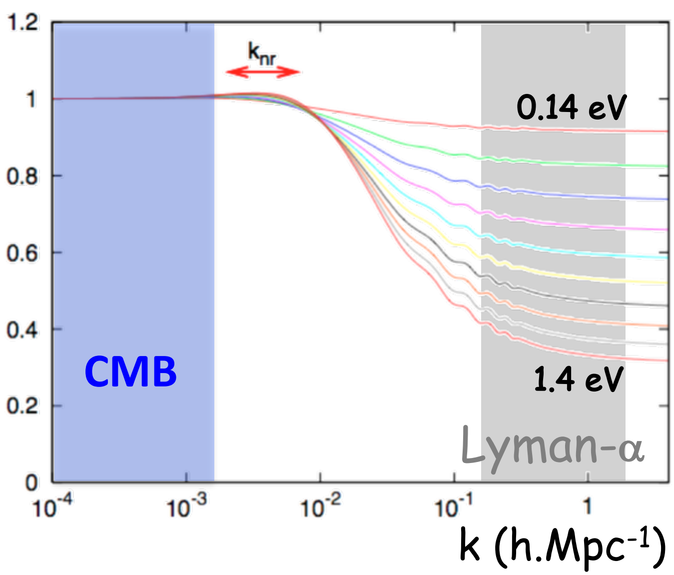

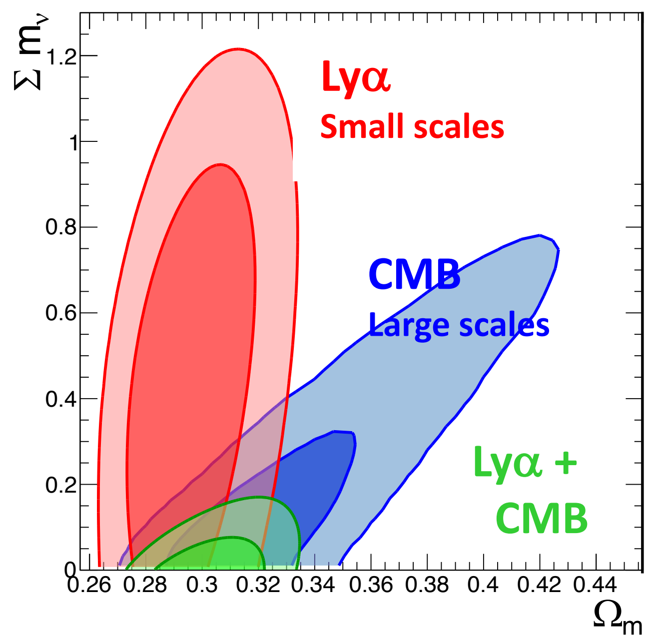

Σm_ν < 0.12 eV

NPD, Yèche, Borde et al. (2015)
NPD, Yèche, Baur, et al. (2015)

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BOSS & Lyman-α

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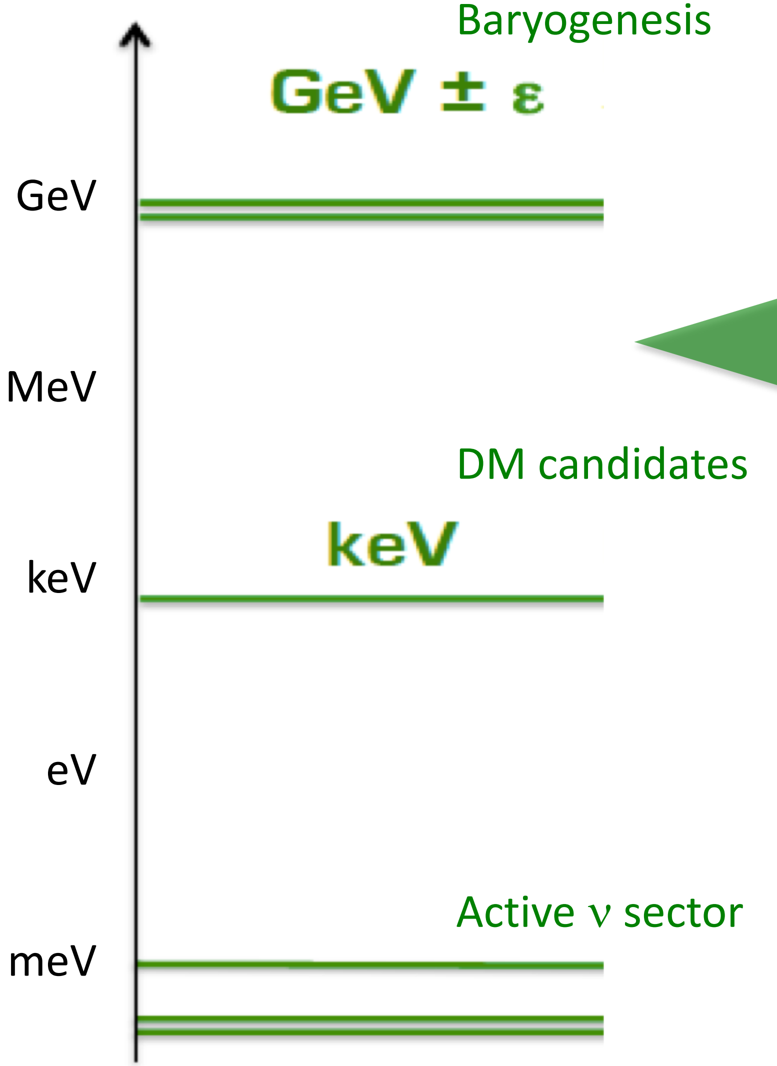
Studying the nature of dark matter

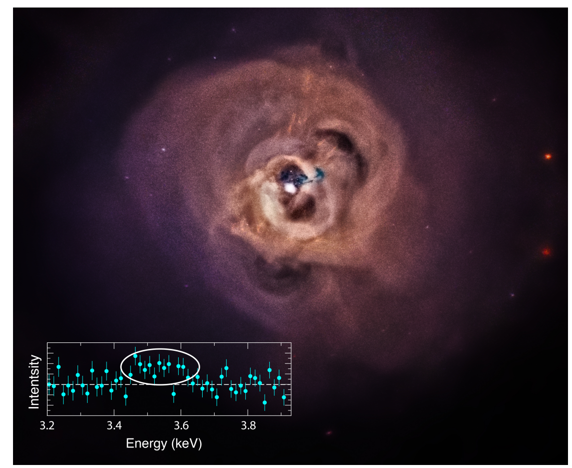
Sterile neutrino sector



Sterile ν sector

ν Minimal Extension

Preseus cluster
Andromeda galaxy
XMM clusters

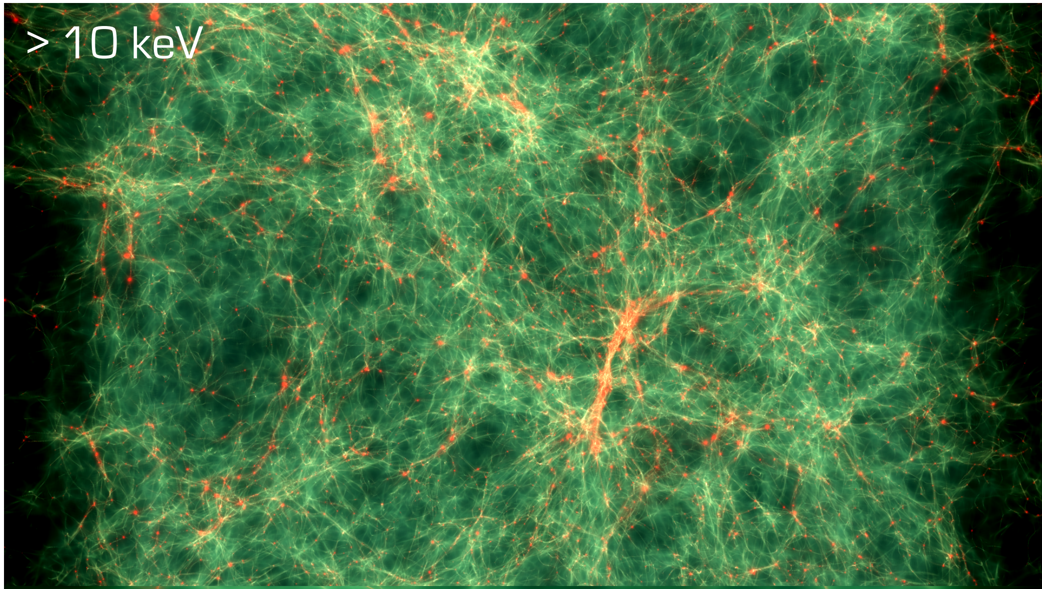


3.5 keV line (XMM): decay of 7 keV ν_s ?

Bulbul++ 2014, Boyarsky++ 2014, Cappelluti++ 2017

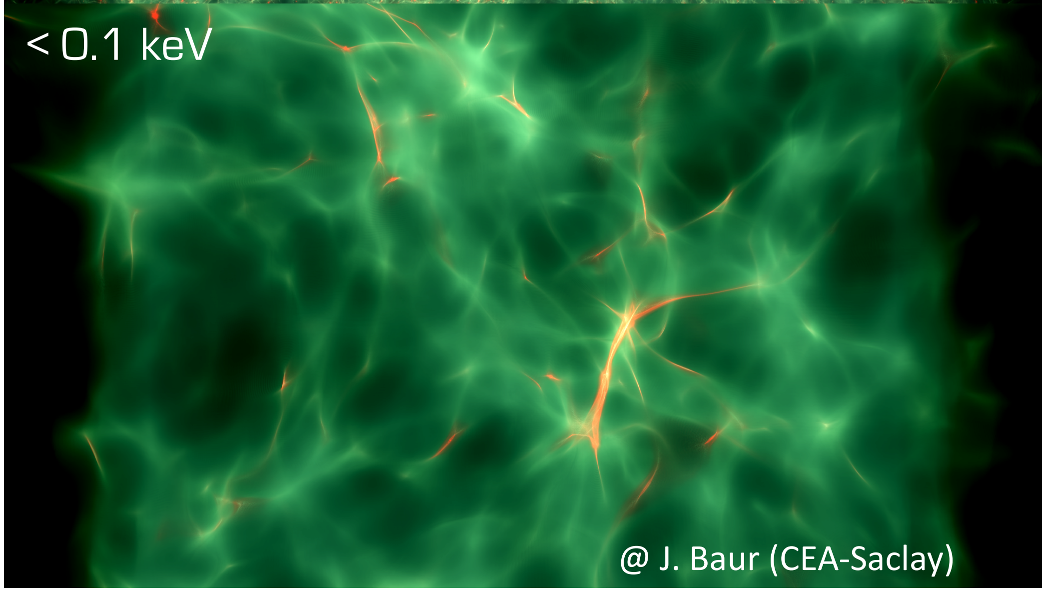
Warm Dark Matter

Cold Dark Matter



If all
dark matter
were

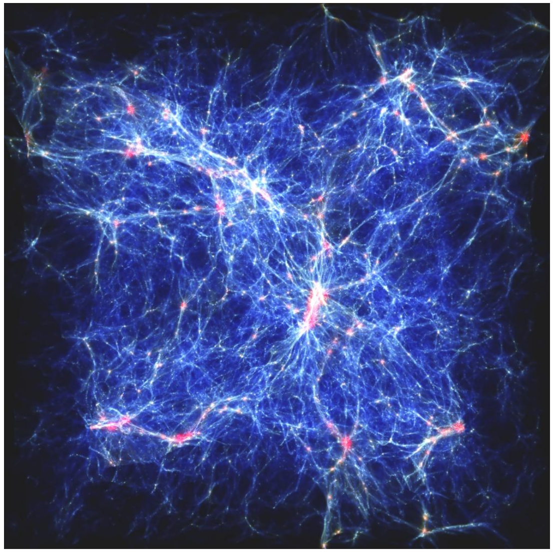
Hot Dark Matter

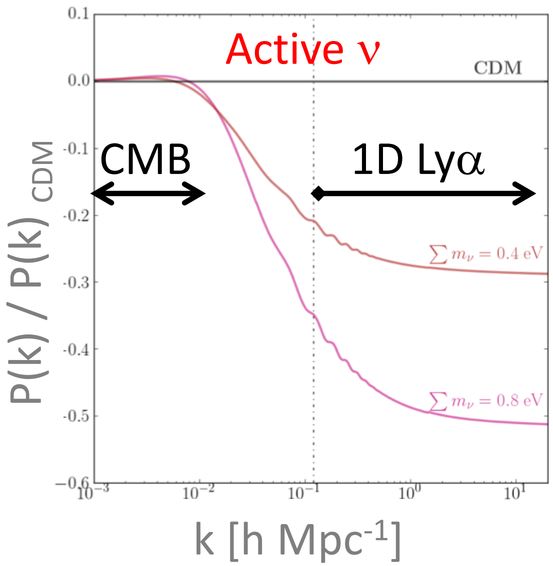


Free Streaming Horizon

$$\lambda^0_{\mathrm{FSH}} = \int_0^{t_0} \frac{\langle v \rangle}{a}\, dt$$

Lyman-α forest and cosmology

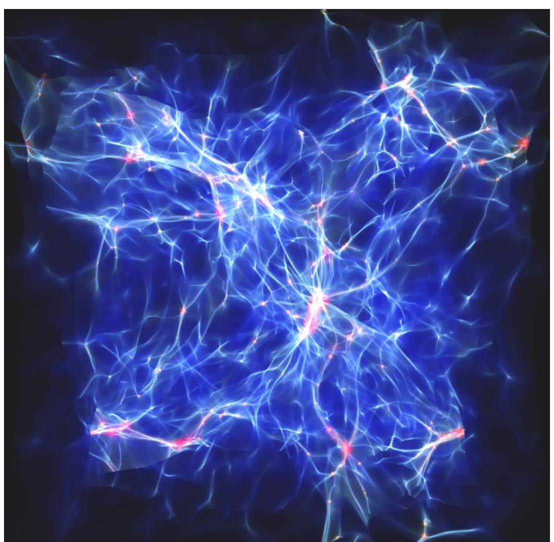


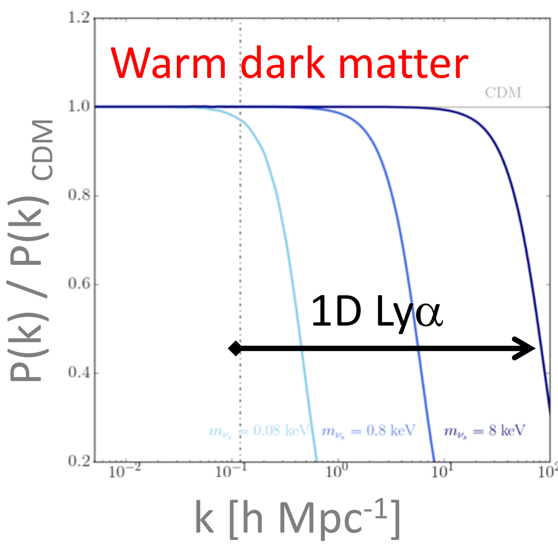


Active neutrinos

- CMB vs. Lyα P(k) comparison
- Greater impact as m_ν increases

⟹ Upper limit on m_ν





Warm dark matter

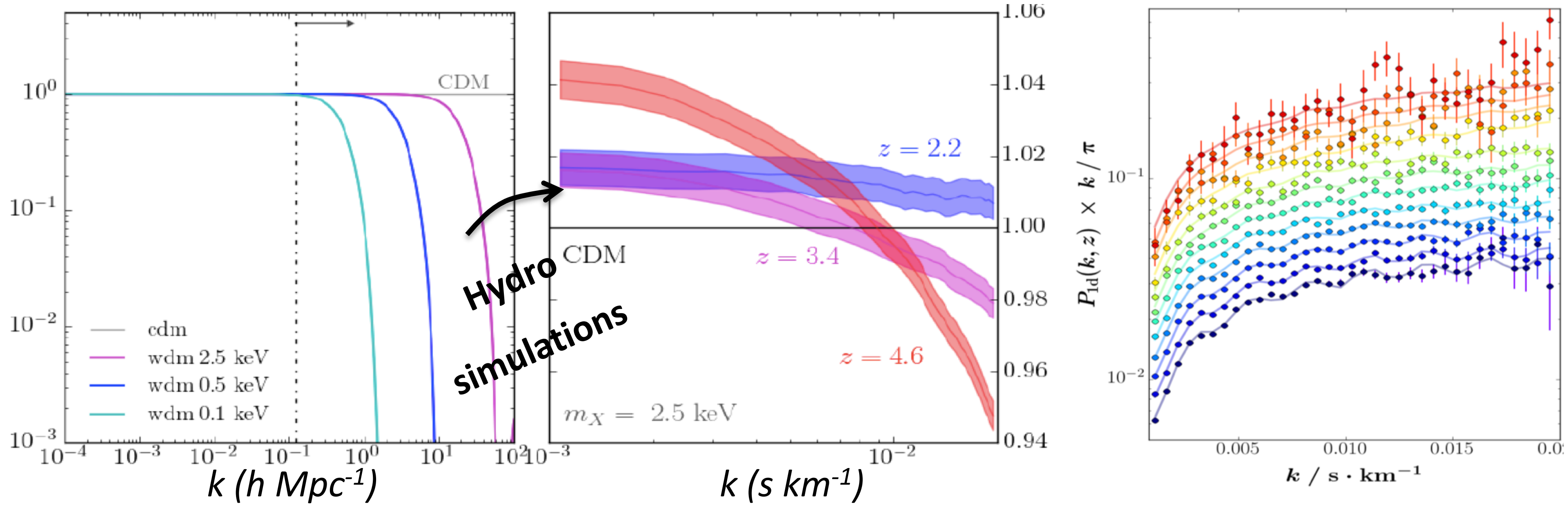
- Power cut-off on small scales
- Greater impact as m_{WDM} decreases

⟹ Lower limit on m_{WDM}

Ly-α forest & WDM

$P_{WDM}(k) / P_{CDM}(k)$ — $P_{Ly\alpha}(k) . k / \pi$

Matter power spectrum — Lyα flux power spectrum — Fit on data



High-z and high-k bins most constraining
(more sensitive to linear regime cutoff)

Warm Dark Matter: thermal relic & NRP ν_s

High-z and high-resolution bins have large constraining power
(closer to linear case, more sensitive to sharp cutoff)

Data Set	BOSS z<4.1	BOSS z<4.5	BOSS + XQ100 + HIRES/MIKE
Lower bound on m_X (keV)	2.97	4.1	4.65 (z≤4.6) [1] / 5.3 (z≤5.4) [2]
Lower bound on m_s (keV)	16.1	24.4	28.8 (z≤4.6) [1] / 34.1 (z≤5.4) [2]

[1] Yèche, NPD+ (2017)
[2] Irsic, Viel+ (2017)

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More conservative

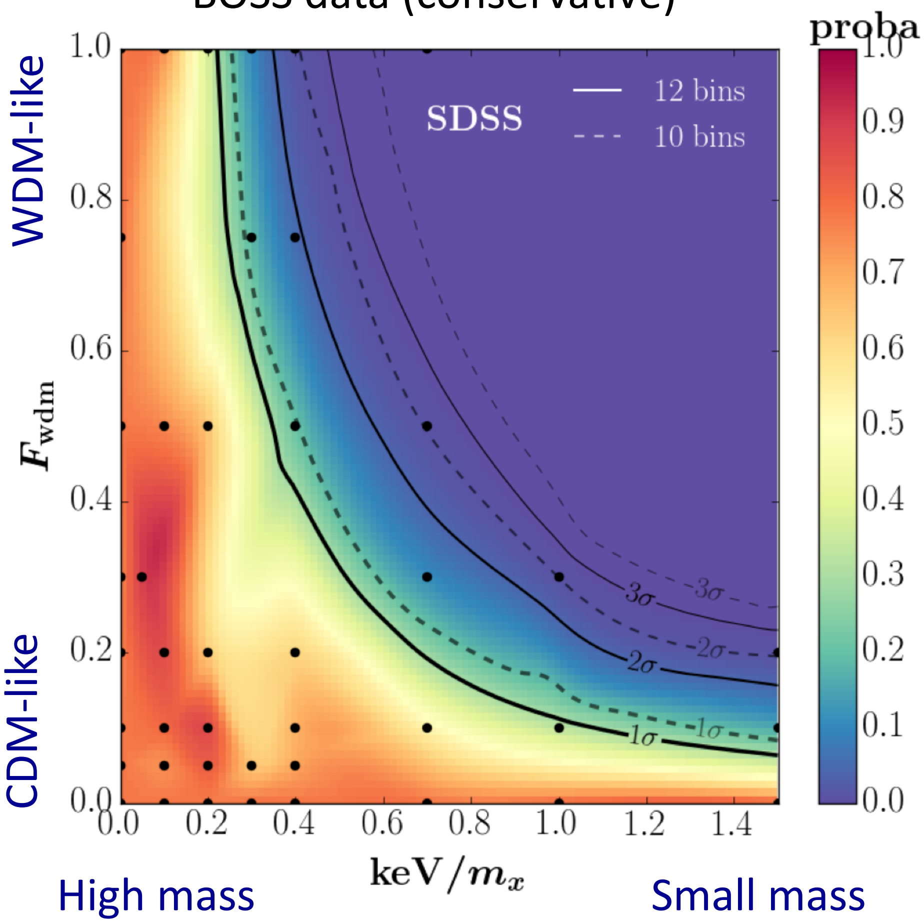
More prone to systematics
(thermal history of IGM)

Among the strongest bound to date

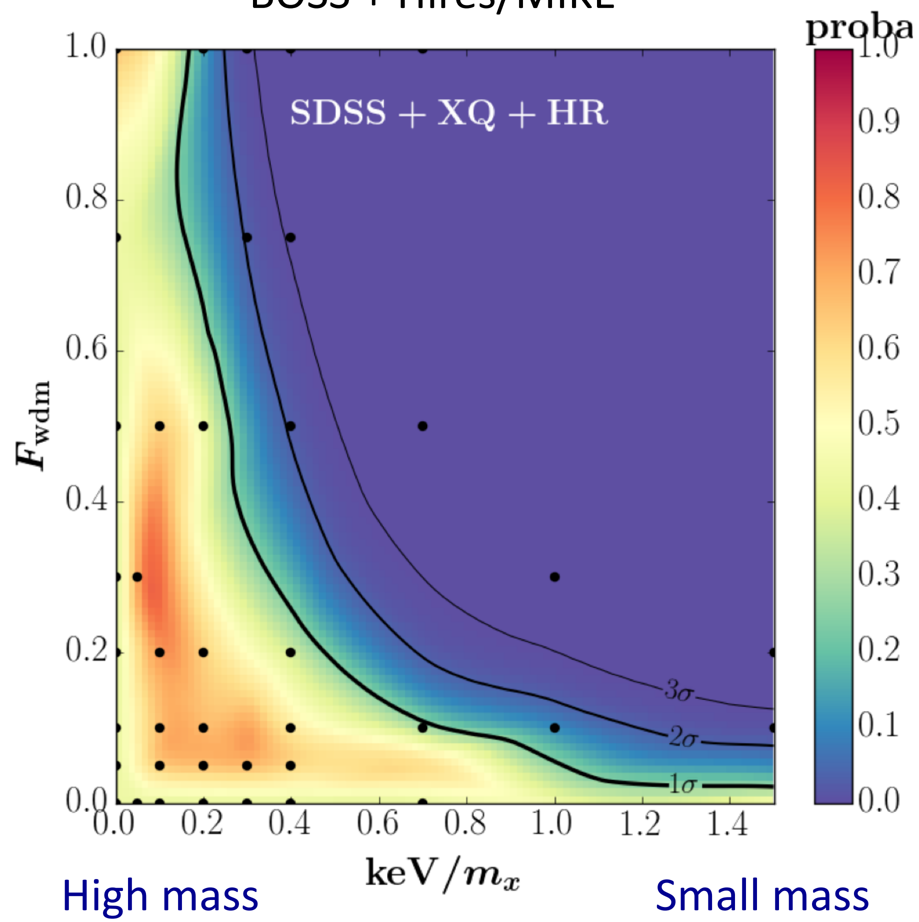
In combination with X-ray data (m_S < 4 keV),
excludes non-resonantly-produced sterile neutrinos

Cold+Warm Dark Matter

BOSS data (conservative)



BOSS + Hires/MIKE



Mixes with high-mass WDM or low WDM fraction are favored
(more CDM-like)

Baur, NPD++ (2017)

Sterile neutrinos: more general scenario

Resonantly produced sterile neutrinos (Shi & Fuller, 1999)

Lepton asymmetry

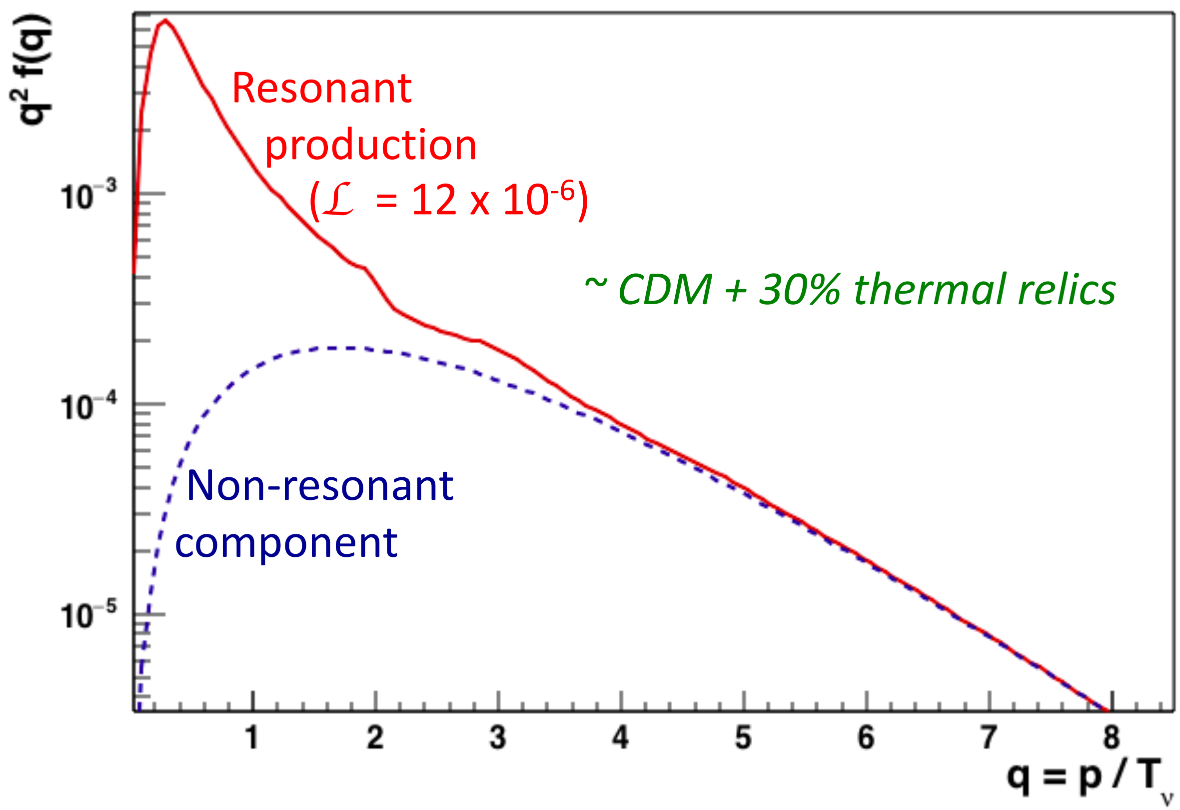
$$\mathcal{L} = \frac{|n_\nu - n_{\bar{\nu}}|}{s}$$

Enhanced oscillations

$$\nu_{e,\mu,\tau} \longleftrightarrow \nu_s$$

Non-thermal distribution
<u>Colder dark matter than</u>
<u>non-resonant production</u>

m_s=4keV Phase-space Distribution

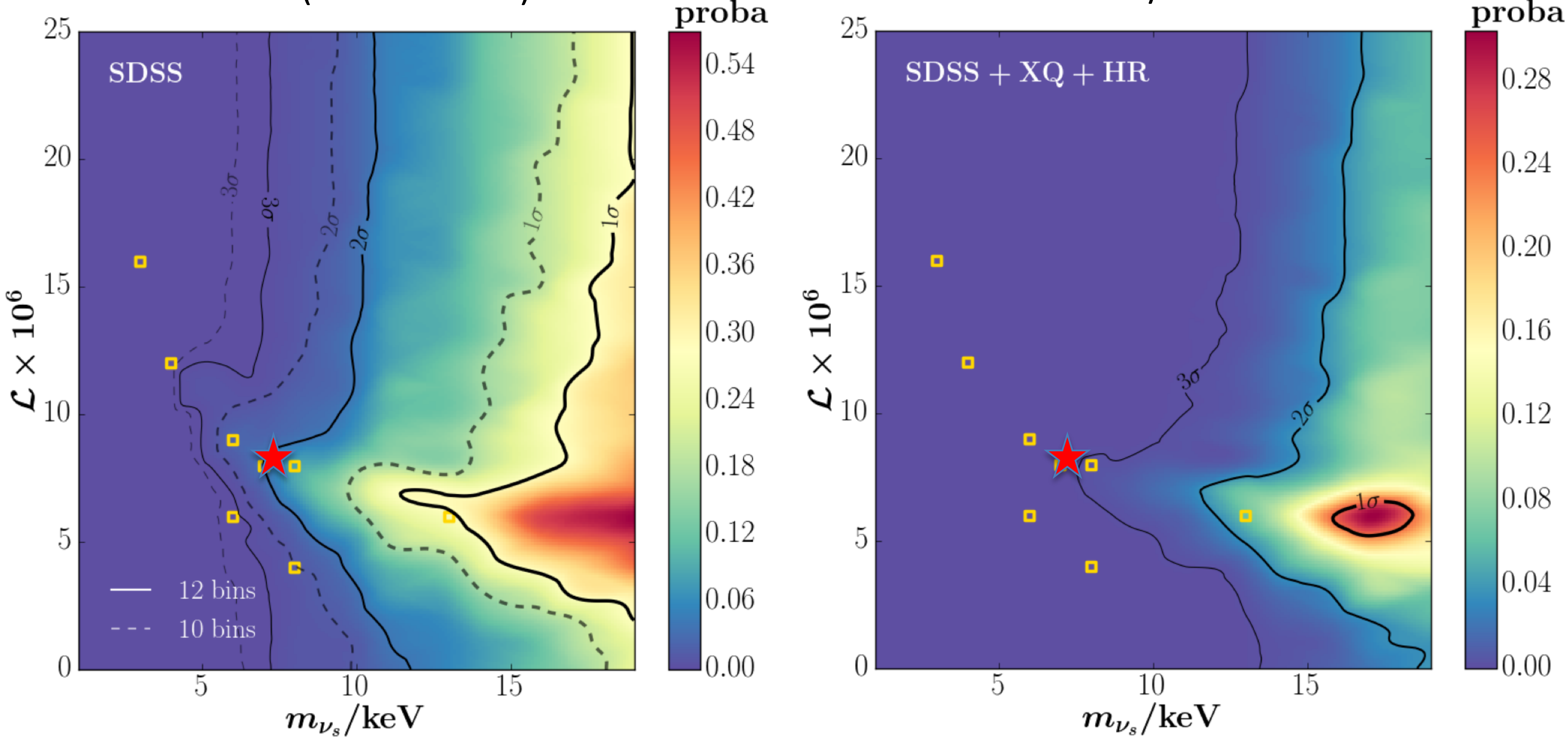


← Cold   Warm →

Resonantly-produced sterile neutrinos

Using C+WDM → non-resonant ν_s mapping at T_{1D} level
+ 8 hydro simulations near coldest models for validation

BOSS data (conservative) | BOSS + Hires/MIKE

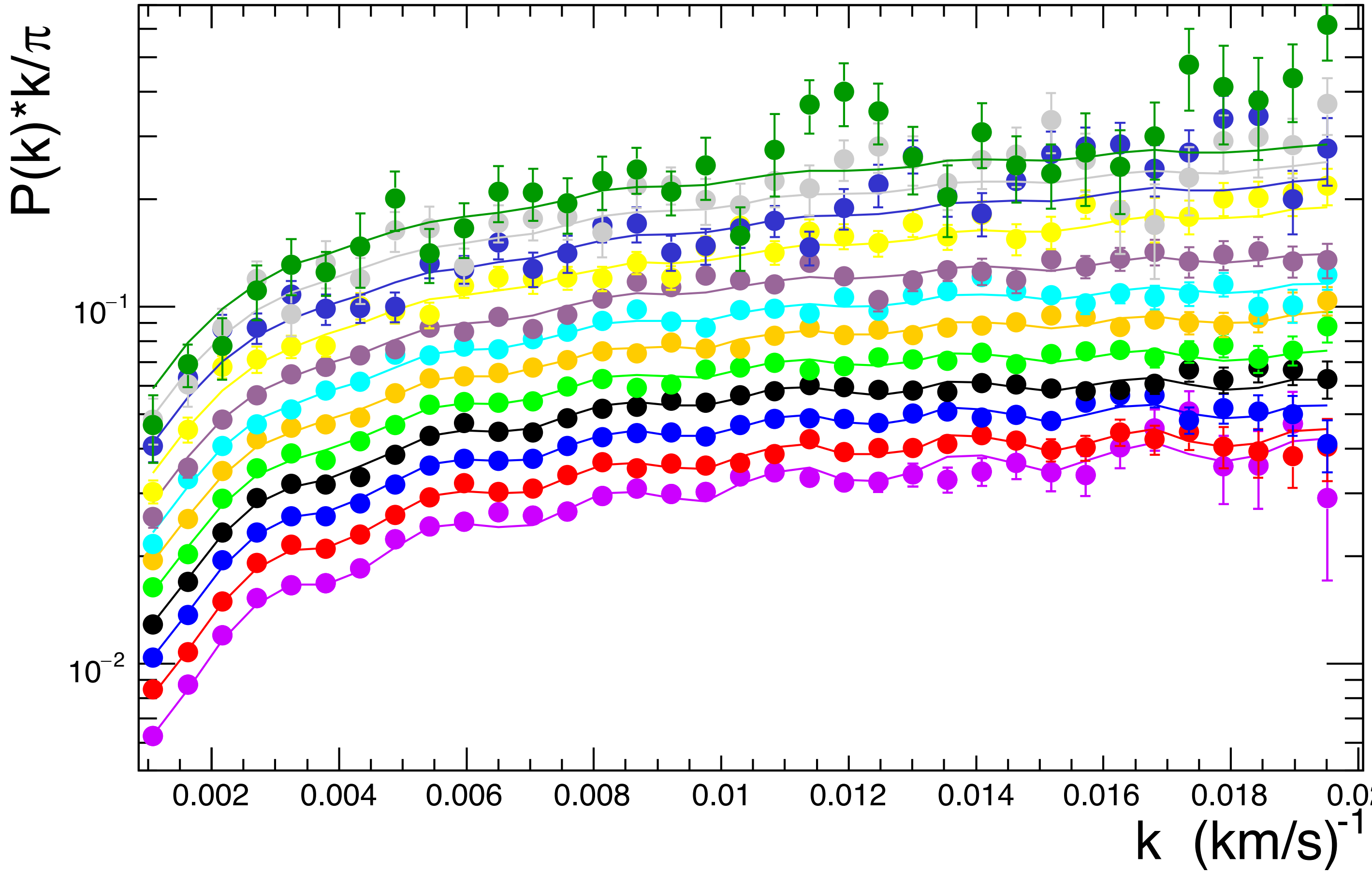


Baur, NPD++ (2017)

And beyond?

Coming soon

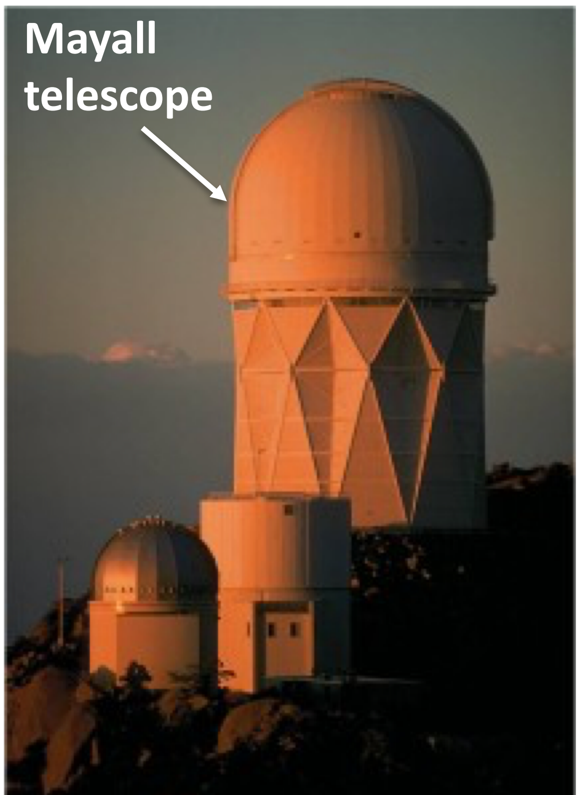
Full BOSS + first year eBOSS: Using best 44k out of 200k quasars

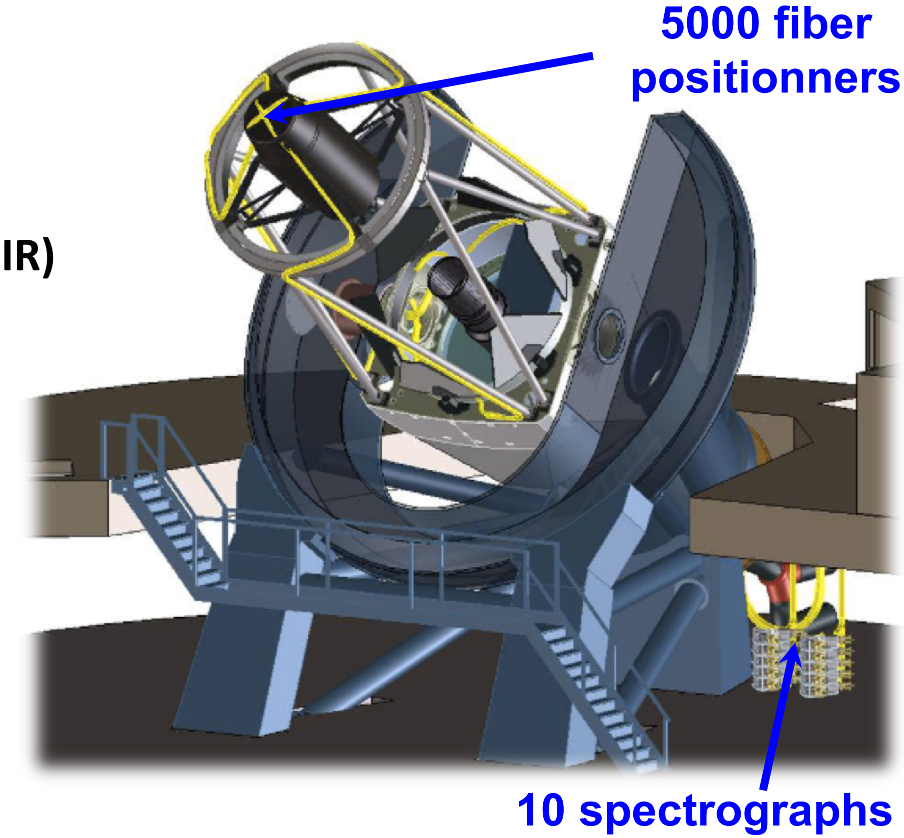


DESI (2020-2025)

DESI instrument

- 4m telescope in Arizona
- 5000 robotic fiber positioners
- 10 spectrographs x 3 bands (B, V, IR)

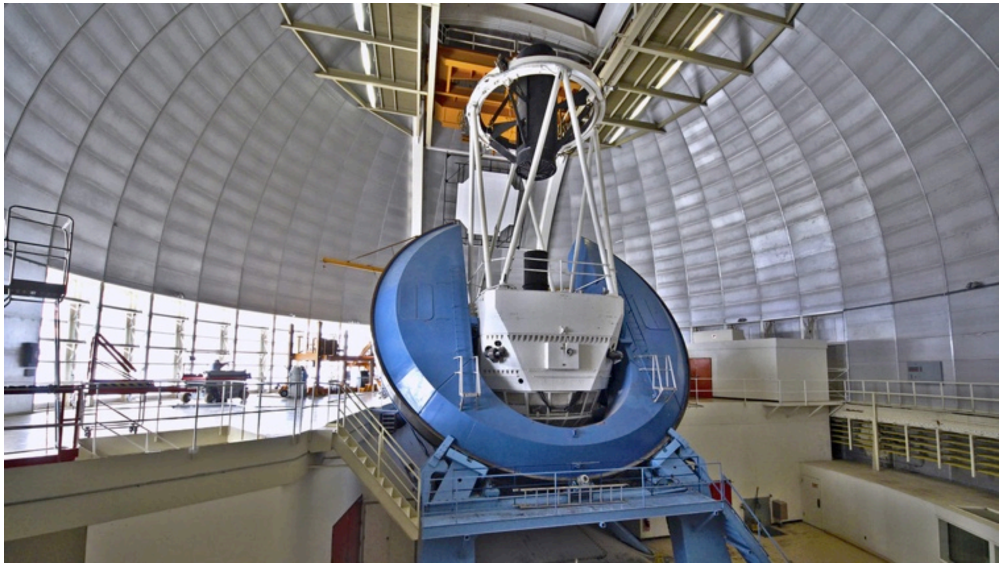


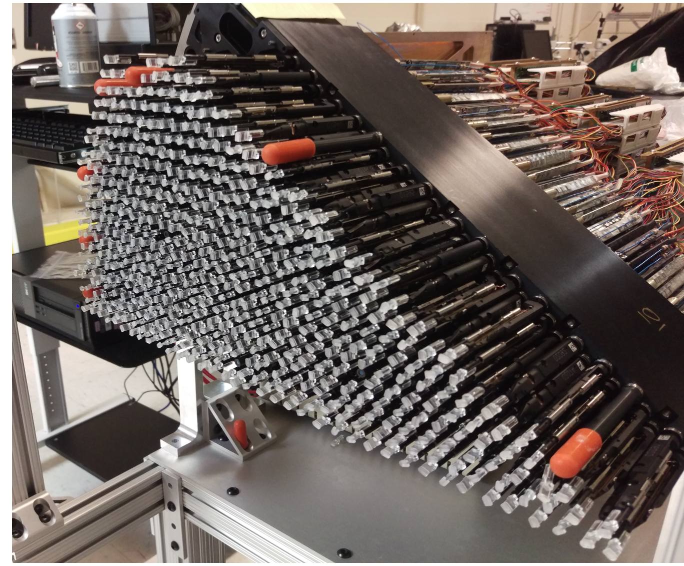


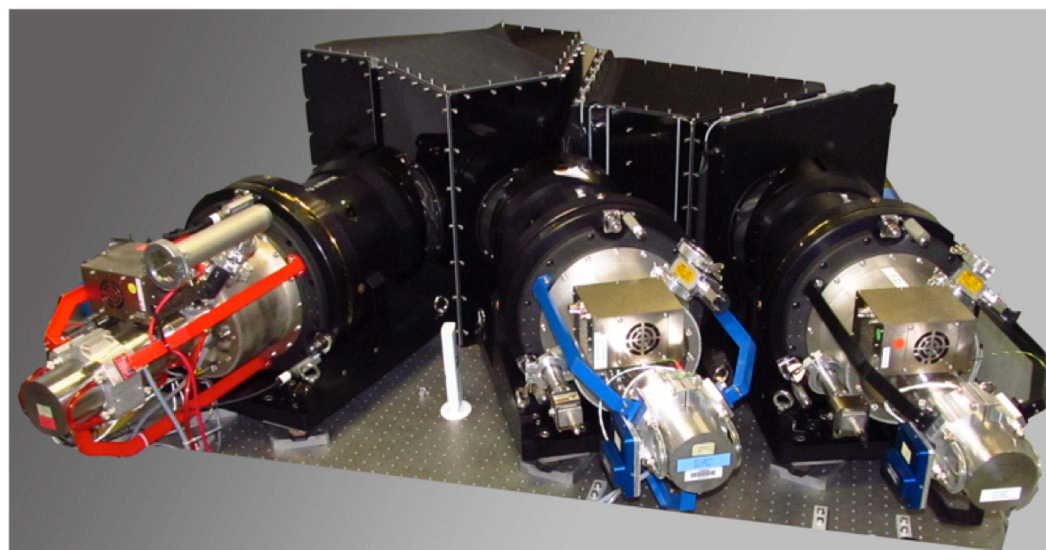
DESI survey

- 14,000 deg^2 spectroscopic survey 0 < z < 4.5 for BAO & RSD
- International collaboration (74 institutes, 46 non-US)
- > 600 members, 40 French engineers & physicists

DESI (2020-2025)







DESI (2020-2025)

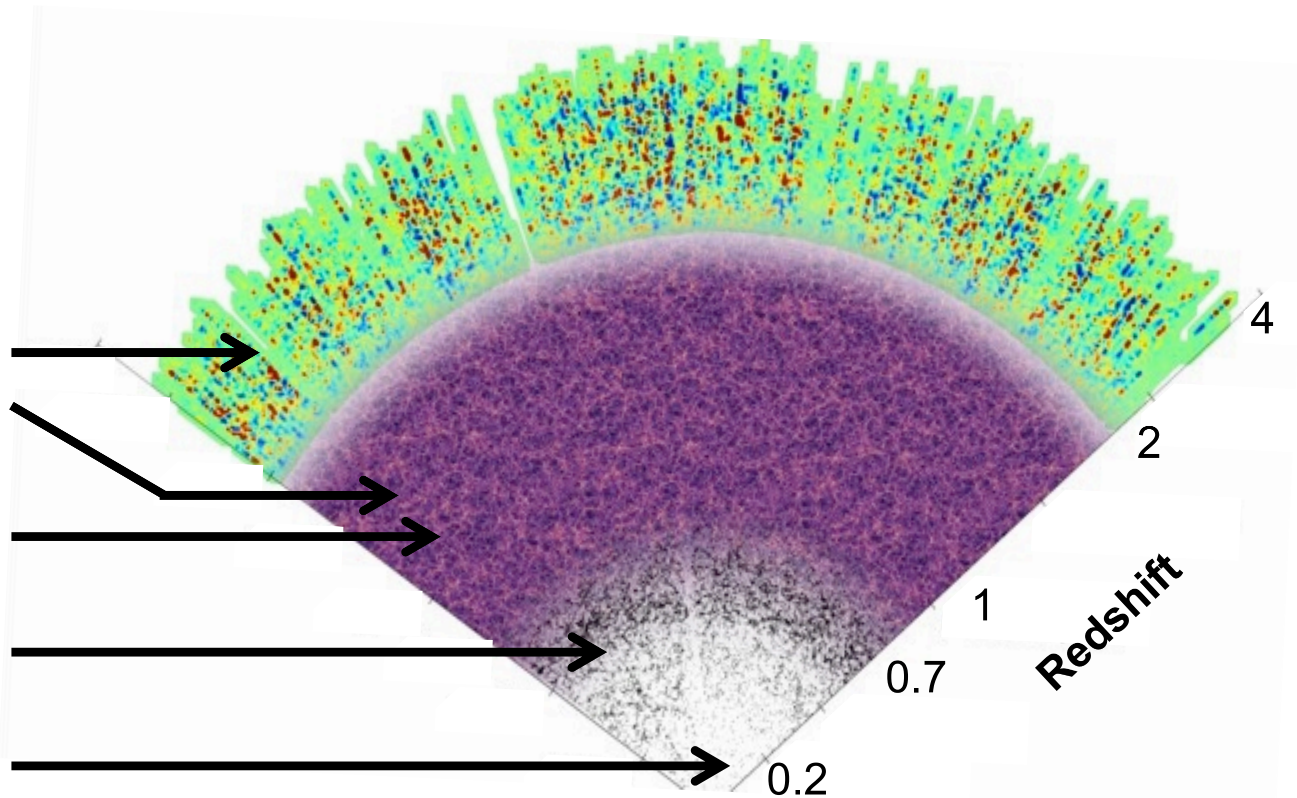
- **Five target classes spanning redshifts z=0.05 → 4.5**
- **35 million redshifts over 14,000 sq. degrees in five years**
- **x30 larger volume than the SDSS map**

2.4 million QSOs
Lyα z > 2.1
Tracers 1.0 < z < 2.1

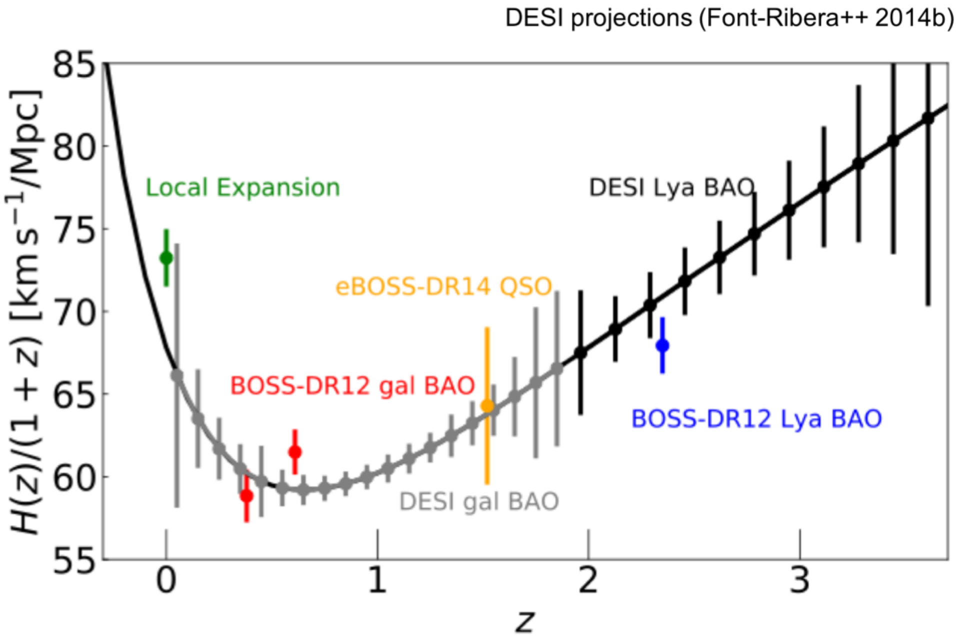
17 million ELGs
0.6 < z < 1.6

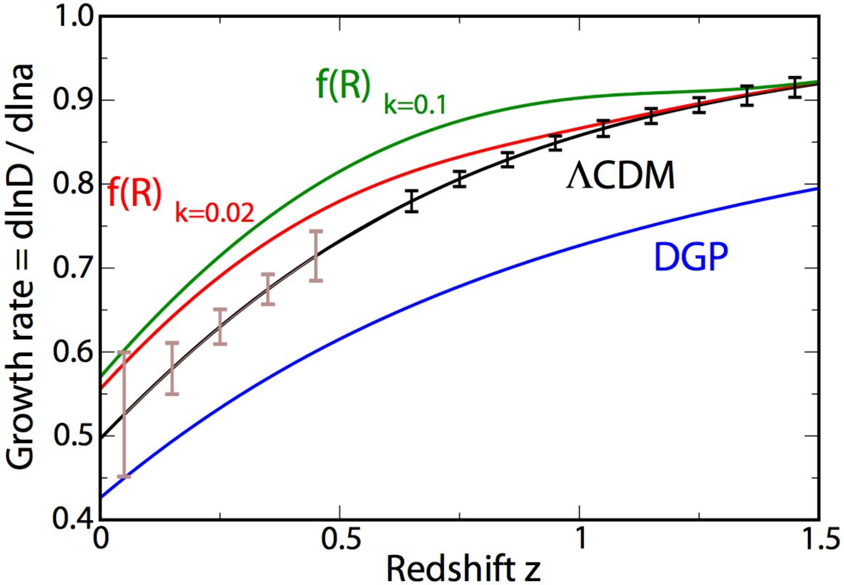
6 million LRGs
0.4 < z < 1.0

10 million brightest galaxies
0.05 < z < 0.4



DESI (2020-2025)





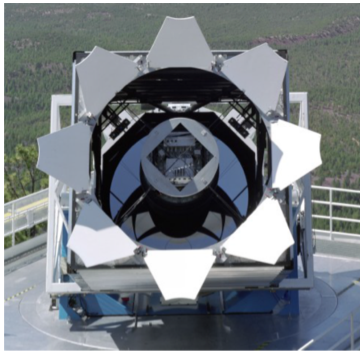
Improvements compared to SDSS

- **BAO:** 1 order of magnitude better $\sigma(a)$ ~ 0.1%
- **RSD:** better than 1% over the full redshift range
- **Neutrino masses:** precision ~20-25 meV on Σm_ν
- **Non-gaussianity (inflation):** $\sigma(f_{NL})$ ~ 5 (DESI-only)

Conclusions

- **Particle physics bounds on neutrino masses: $0.06 < \Sigma m < 6$ eV**

- **Constraint on mass of active neutrinos**
  - **Sum of neutrino masses $\Sigma m_\nu < 0.12$ eV** (95% CL) **from Lyα+CMB**



- **Constraint on warm dark matter & sterile neutrinos**
  - **m_s (rnon-esonantly produced) excluded**
  - **m_s (resonantly produced) in conflict**
    with sterile ν interpretation of 3.5 keV X-ray line

- **Prospects**
  - **Update with full SDSS BOSS + eBOSS**
  - **Planck + DESI Lyα $\sigma(\Sigma m_\nu) = 0.039$ eV**
  - **Planck + DESI Galaxy $\sigma(\Sigma m_\nu) = 0.024$ eV**